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THE GEOLOGY OF THE BRADEN MINE, RANCAGUA, CHILE.[1]

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INTRODUCTION.

Among the copper deposits of South America there are two types that stand out prominently. The first is characterized by the association of quartz, enargite and pyrite. To these belong the occurrences at Cerro de Pasco, Chuquicamata, Famatina and many others. The second type carries quartz, tourmaline, pyrite

[1] Presented before the Society of Economic Geologists, Amherst Meeting, Dec. 28, 1921.

and chalcopyrite. Examples of this type are more common in Chile than elsewhere and among them we mention Tamaya, Las Condes, Peralillo and Braden.

The Braden mine seems to be the unique example of a copper deposit lying in and about a large explosive volcanic vent. It furnishes one of the most striking evidences on record of the intimate connection in origin between certain mineralizing solutions and bodies of igneous rock, for in the Braden crater, rising mineralizing solutions and ascending masses of igneous rock followed the same paths and alternated with each other. The geologic history is not only unusual, but is also complex, comprising three periods of igneous intrusion, three periods of mineralization by ascending solutions, uplift and tilting of the land, erosion of the surface and enrichment of the ores by waters descending from the surface, and other events.

The writers are indebted to so many of the company's officials in New York and in Chile for courtesies in the progress of the work that it is impossible to ackowledge by name all these obligations, but especial acknowledgment is due to Messrs. S. S. Sorensen, general manager, and Horace R. Graham, superintendent of mines. Mr. William S. Connor and Mr. Lloyd E. Le Duc, of the engineering staff, efficiently aided us as field and office assistants throughout most of the survey.

General Situation.—The Braden mine, or El Mineral Teniente, as the Chileans call it, is situated in the Western Cordillera of Chile thirty miles northeast of Rancagua, a town a couple of hours ride by train south of Santiago. It lies on the south slope of the upper valley of the Teniente River, a small tributary of the Coya, which again empties into the Cachapoal River. The railroad from Rancagua leads steadily upwards following the torrential streams till the mine is reached. The slopes are covered by brush and small trees within a few miles of the mine; beyond this there is little or no vegetation, and the whole region becomes Alpine in aspect with plenty of evidence of a former glaciation. At the mine the elevations range from 7,458 to 9,642 feet and a few miles east of the mine the divide is reached at an elevation of

11,800 feet. Beyond this lies the longitudinal valley of the Maipu, beyond which, twenty-eight miles from the mine, rises the main snow-covered divide of the Western Cordillera with elevations of up to 18,000 feet. Up to within two miles of the mine the range is built of Tertiary effusive rocks, alternating with tuffs and tuff breccias—the Cerro Negro series referred to below.

GEOLOGIC HISTORY OF THE BRADEN MINE.

The geologic history of the Braden mine is essentially a record of alternating igneous activity and ore deposition, and affords convincing evidence of the intimate genetic connection between igneous rocks and ore deposits. (Figs. 10 and 11.)

The Cerro Negro Series.—The first event recorded in the rocks of the vicinity of the Braden mine is the eruption of a great series of volcanic rocks now forming the rudely bedded series of Cerro Negro, the Caletones cliffs and the valley of the Puquios. The writers have termed these the Cerro Negro series. The volcanic mountains, probably several in number, from which these rocks were erupted have been so dissected by stream erosion that detailed geological studies covering large areas would be needed to discover even their whereabouts. The rocks of this series are all products of volcanic eruption; "flows" or sheets of lava poured out upon the surface from volcanic vents, alternating with "tuffs" or beds of lava fragments showered down during the eruptions. In age they are probably Tertiary, and they constitute the oldest known formation of the district, antedating the formation of the Braden crater and of the ore deposits. Mineralization of the series is mainly confined to scattered veins of negligible commercial importance, some of which were formed prior to the main mineralization of the Braden mine, while others may be contemporaneous with it. Epidote and other secondary products often appear in these lavas.

Intrusions of Andesite Porphyry.—Into this volcanic series there was later forced from below a great mass of molten rock which displaced and pried apart the beds of the older rock and solidified to form andesite porphyry, where it cooled rapidly,

and quartz diorites, where its cooling was more leisurely. Complete gradations are traceable from the andesite porphyries into quartz diorites. These two types of rock are similar in mineral and chemical composition, and their difference in name is chiefly a matter of texture. Because the andesite porphyries are more abundant than the quartz diorites in the mine workings, and because the name andesite has long been applied to these rocks in the company reports, it is best to use "Intrusive Andesite Porphyry" as a comprehensive name for the formation.

The series constitutes a belt from about 1.5 to 5.5 kilometers wide, which has been traced from the so-called "Gypsum Mine" northeast of the "crater" to the Caletones cliffs, as is shown in

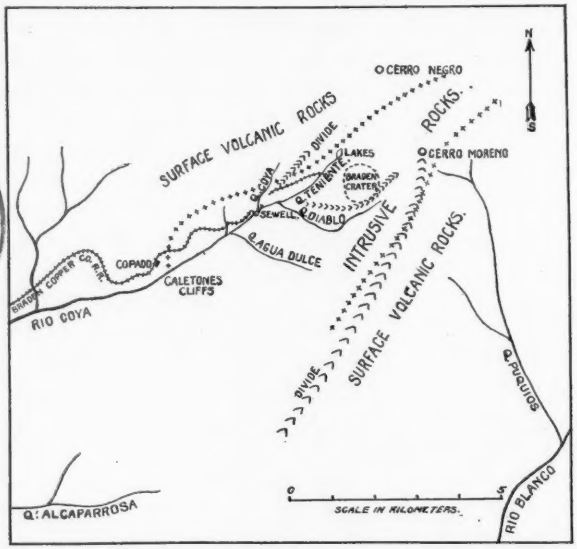

FIG. 10. Map showing the general location of the Braden "Crater" and the approximate limits of the intrusive Andesite Porphyry-Quartz Diorite mass.

Fig. 10. The further extent of these rocks northeast and southwest is not known. They are bounded on the northwest and

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southeast by the surface volcanic rocks of the Cerro Negro series.

At its borders the andesite-diorite mass sends off wedge-like branches or sills which split apart the beds of the bordering Cerro Negro series. These branches can be clearly traced into continuity with the main body of andesite-diorite, and are similar to it in composition. These relations can be best seen near the divide between Canyon Diablo and the Puquios Valley, and less perfectly in the cliffs at Caletones, and they show that the andesite porphyries and quartz diorites are intrusive rocks, or, in other words, were forced from below in a molten condition into the older rocks of the Cerro Negro series. Their intrusive origin is further demonstrated by their coarseness of grain in many localities, a feature indicative of comparatively slow cooling under a cover of other rocks.

While showing variations in coarseness and local brecciation, the rocks of this series do not show flow lines, spherulites, amygdaloidal structure, or other features characteristic of surface volcanic rocks, and no tuffs are interbedded with them. In these respects they contrast greatly with the bordering Cerro Negro series.

The andesite porphyry is a dark greenish gray rock with phenocrysts of andesine-labradorite from 2 mm. upwards in length. There are chloritized pseudomorphs after augite. Chlorite is usually well distributed through the rock. The groundmass is fine-grained but holocrystalline, usually of small feldspar prisms with interstitial quartz. Sometimes it is trachytic by the predominance of elongated feldspar prisms.

First or Pre-explosion Period of Mineralization.—During the earth movements that were gradually uplifting the Cordillera region the intrusive andesite porphyry mass that has just been described became fractured, bleached, and tourmalinized over considerable areas and locally slightly mineralized with pyrite.

The andesite porphyries and quartz diorites have in many places been so completely altered that their original character can only be proven by gradations from the altered into the fresh

types. This alteration was accompanied by sparse deposition of sulphides and constitutes the first period of mineralization. The earliest alteration consists in the development of magnetite in dark cloudlike masses and of disseminated dirty brown small foils of biotite. The rock then becomes strongly chloritized, with more or less sericite, both attacking the dark silicates and the feldspars. The groundmass is more or less silicified, sometimes it is converted into a mosaic of small quartz grains. Rutile is abundant in many sections. Lastly tourmaline develops, replacing all the other secondary minerals as well as the feldspars. In hand specimens, the tourmaline is black and is developed in small needles or radiating masses. In thin section it is blue gray to almost colorless. Strong development of sericite leads to bleaching of the rock and in the most altered specimen the chlorite has disappeared and the entire rock is a confused aggregate of quartz and sericite.

The development of black tourmaline is a usual but not invariable accompaniment of the bleaching. Quite commonly it coats fractures or replaces the rock along incipient fractures, forming veinlets within definite borders. In brecciated parts of the andesite porphyry the matrix of the breccia was the first part to be tourmalinized. Typical breccias of this origin show white to cream colored fragments of altered andesite porphyry in a dark gray to black matrix. In more highly tourmalinized breccias the fragments are partly tourmalinized; in some cases the original feldspar phenocrysts remain only as white spots still untouched. Finally, the entire rock, fragments and matrix, may become a black mass almost wholly tourmaline.

The bleached and tourmalinized areas, although irregular in size, form and distribution, are found throughout the entire observed length of the intrusive mass. The conspicuous light color of large areas on the ridges southeast of Sewell is due to this alteration. A few miles north of the mine a small but conspicuous black knob consists of the brecciated andesite porphyry largely replaced by black tourmaline. In the immediate vicinity

of the Braden mine the altered areas are mainly on the east and northeast sides of the "crater." The so-called "Gypsum Cliffs," about 1 kilometer northeast of the "crater," are a further example. In many places it is difficult to determine what factors have controlled the distribution of the alteration, but generally it seems to have followed fracture zones of prevailing northeast trend, paralleling the quartz veins described below. The transitions from fresh to highly altered rock may take place within surprisingly short intervals, frequently in a few tenths of a meter, and in a space of 100 meters there may be several alternations of altered and fresh rock.

Pyritic Quartz Veins.—The quartz veins of the mine and its vicinity appear to be another phase of the first mineralization. They range in width from a few centimeters to 5 or 6 meters and commonly have north to northeast strikes and steep dips. On the surface, notably in the vicinity of Fortuna No. 2 gulch, they stand up like ragged rusty walls above the surface of the bordering andesite porphyry. A few consist wholly of white quartz, but in the majority black tourmaline, pyrite and chalcopyrite are present. Nowhere were the sulphides of this mineralization deposited in sufficient abundance to form ore.

The bleaching and local brecciation of the andesite porphyry and the formation of the quartz veins antedated the formation of the Braden crater, and there is no regular relation whatever between the distribution of altered andesite porphyry and quartz veins and the form or position of the crater. The quartz veins abruptly terminate where the andesite porphyry of the crater walls gives place to the breccias and tuffs that occupy its central portion.

The Formation of the Braden Explosive Vent.—The event of supreme importance in the geologic history of the mine was the great explosion which produced a volcanic vent and shattered the bordering andesite porphyry in such a manner as to provide ample open spaces for the deposition, somewhat later, of ore minerals. This explosion was probably caused by the upward progress of a body of molten and partly molten rock beneath the present vent.

A sudden upward pulsation of this hot mass, bringing it into contact with portions of the andesite-diorite mass that lay nearer to the surface and whose fractures were filled with ground water, and the violent conversion of this water into steam was the probable cause of the explosive eruption. The gases imprisoned in the magma itself were probably a coöperating factor in the explosion.

The vent produced was certainly more than 1,000 meters in depth and probably nearer 2,000 meters, and about 1,000 meters in average width, tapering somewhat from top to bottom. The material erupted consisted mainly of fragments of the andesite porphyry mass that formed the crater walls mingled with smaller numbers of fragments of alkali porphyries (dacite porphyry, granite porphyry, and latite porphyry) that apparently represent the upper parts of the intrusive mass that produced the explosion and were shattered by it (Fig. 13).

The eruption appears to have been solely an explosive shattering of rocks already solidified. No molten or partly molten rock was ejected from the vent as lava flows or showers of pumice, and it is probable that steam was the principal gas given off. The debris of the eruption in part fell back into the vent filling its lower portion, but most of it was probably strewn over the surface bordering the crater mouth.

Next ensued a period of quiescence as regards eruptive activity during which surface processes assumed the leading rôle in the development of the geology of the mine. There are evidences that at this time the depression produced by the explosion became converted into a lake (see Fig. 11), while at the same time rains and freshets gradually washed back into the hole part of the debris which the eruption had strewn over the surface. During its redeposition within the vent much of this debris acquired a bedded structure; beds of fine material alternating with coarse fragments, and many of the fragments became partially rounded, in fact, the evidence of the existence of a lake consists in this bedding and the rounding of the fragments. This filling constitutes the Braden tuff, of which a thickness of approximately 800 meters is now in view between the highest exposures in the

upper part of the "crater" and the lowest exposures in the deepest mine workings. (See Fig. 12.)

At the close of these events there existed a cylindrical body of Braden tuff, filling the crater and bordered by fractured

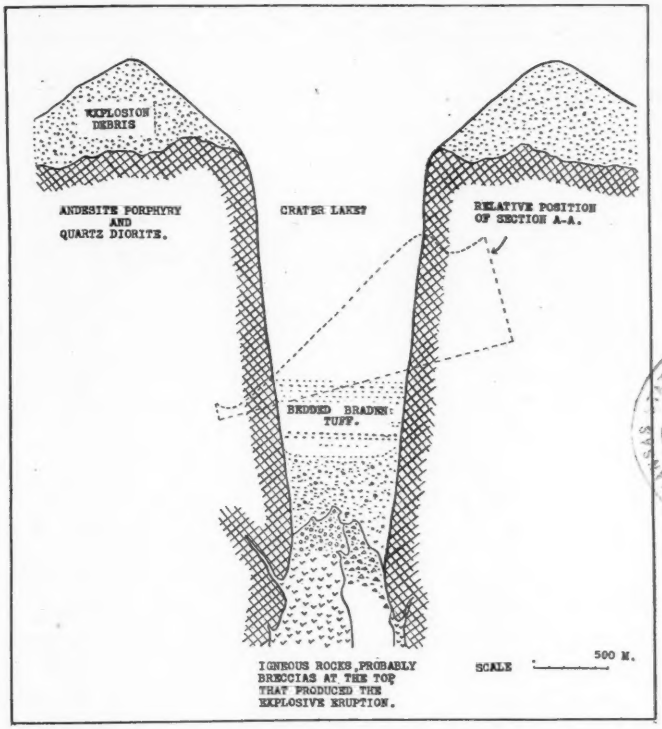
EXPLOSION DEBRIS
ANDESITE PORPHYRY AND QUARTZ DIORITE.
CRATER LAKE?
RELATIVE POSITION OF SECTION A-A.
BEDDED BRADEN TUFF.
IGNEOUS ROCKS, PROBABLY BRECCIAS AT THE TOP THAT PRODUCED THE EXPLOSIVE ERUPTION.
SCALE
500 M.

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FIG. 11. Idealized reconstruction of the Braden "Crater" not long after the explosion when some of the debris from the explosion had fallen back and had been washed back into the vent. Bedding in some of the Braden Tuff suggests that a lake occupied the vent at this period.

andesite porphyry. These rocks extended farther upward than their present exposures for they have subsequently been cut down by erosion to an unknown but probably considerable extent. It is also probable that they were at this time buried under other rocks

whose character is unknown, for the rocks and ore minerals which in the events next to be described were brought into the position of the present Braden mine lack the features usually found in ore and rocks crystallized at or close to the surface.[1]

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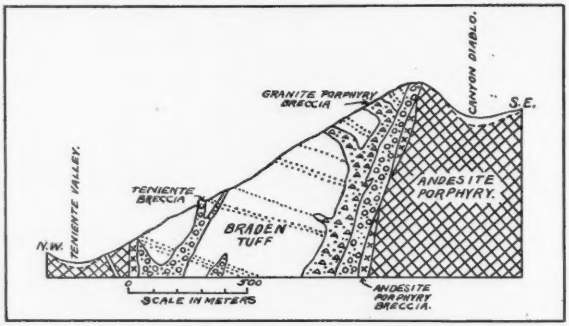

FIG. 12. Generalized cross section (*A–A*) of the Braden "Crater" today —after (1) a second intrusion of the igneous rocks from beneath the crater to higher levels than before, (2) tilting of the land to the southwest, and (3) lowering of the surface by erosion. The position of this section with respect to the earlier stage in crater development is indicated by the broken lines in Fig. 11.

Second or Main Period of Primary Mineralization.—The explosive eruption which formed the Braden vent greatly shattered the andesite porphyry composing its periphery. The shattering, as might be expected, was exceedingly irregular, fracture planes trending in every conceivable direction, though in a few localities a predominant trend, parallel to the crater wall, is discernible. The width of the zone of most intense shattering is uneven, ranging from 100 and 200 meters to more than 600 meters, the widest portions being on the northeast side of the crater.

After the interval, during which the crater became filled with the Braden tuffs, mineralizing solutions, rising principally about

[1] The literature contains many examples of explosion vents more or less similar to the "crater" of the Braden mine. Some examples are the occurrences in Scotland, those described from the Suabian highlands in Germany, and also the explosion vent of Cripple Creek, Colorado, in which the steep or even overhanging walls have been exposed by mine workings. In the last case, however, the mineralization with gold tellurides followed shortly after the close of the volcanic activity.

the periphery of the old vent, deposited quartz, tourmaline, biotite, pyrite and chalcopyrite in irregular fractures in the andesite porphyry and formed large bodies of mineralized material with a copper content in most places of between 0.50 and 1.50 per cent., though locally slightly richer. Thus was initiated the formation of the great ore bodies that are the main resource of the Braden mine, but, as later explained, their enrichment by descending secondary mineralization was necessary to raise their copper content to a workable grade.

Although the Braden tuffs certainly occupied the vent of the old crater at the time of this mineralization, they were almost nowhere mineralized to the extent of more than 0.50 per cent. of copper. That they were penetrated by the mineralizing solutions is shown by the almost universal presence in them of scattered fine grains of pyrite and chalcopyrite, but because of their somewhat clayey matrix, and the nearly complete absence of fracture planes, they were not a favorable locus for ore deposition.

The ores of the second period are andesite porphyry traversed by veinlets of ore minerals from a millimeter or less up to a centimeter, or rarely 2 or 3 centimeters in width. Within the ore bodies there are seldom less than a dozen such veinlets in a meter's length of andesite porphyry. Between the veinlets the andesite porphyry commonly carries scattered small grains of sulphides, but more than 90 per cent. of the copper is undoubtedly in the veinlets. The ores commonly break readily into small blocks along the sulphide veinlets, a characteristic favoring cheap mining.

The predominant ore minerals of this period are quartz, pyrite and chalcopyrite; black tourmaline though nearly universally present is subordinate in amount; biotite was noted only in a few places and in very minor amounts, but was clearly contemporaneous with the sulphides. The relative abundance of the three principal minerals varies considerably even in adjacent veinlets; quartz is abundant in some and almost absent from others; pyrite is the dominant sulphide in some and chalcopyrite in others. Commonly the several ore minerals are irregularly associated,

but in some veinlets the quartz is mostly next to the walls and the sulphides in the center.

Of much economic importance is the tendency for pyrite to increase and for chalcopyrite to decrease in relative abundance outward in all directions from the periphery of the crater. In many of the crosscuts into the footwall the passage from ore to material below workable grade is practically coincident with the transition from predominant chalcopyrite (somewhat enriched) to predominant pyrite.

Intrusion of Alkali Porphyries and Breccias.—The next event in the complex history was the intrusion of masses of molten rock which crystallized as dikes and irregular bodies of dacite porphyry, and of bodies of partly or wholly solidified and brecciated dacite and latite porphyries, giving rise to what has been termed the Teniente breccia. These intrusive masses are confined, so far as known, to the " crater " or its near vicinity. The Teniente breccia forms a nearly continuous sheath between the filling of Braden tuff and the andesite porphyry of the " crater " walls, sending off, however, irregular ramifications into the central portions of the tuff mass. A single outlying body of Teniente breccia occurs in the andesite porphyry shortly south of the vent near the divide between Teniente valley and Canyon Diablo. The details of surface distribution are shown on the geologic map (Fig. 13). This locality, by reason of the explosive eruption and the other events already described, was a weakened area that could be readily penetrated by bodies of intrusive rock, but a further explanation of the localization of these rocks near the vent is probably to be found in their derivation from the same deep source as the body of magma that produced the crater explosion. Evidence for this belief is found in the identity of the porphyries intruded at this time, in appearance and composition, with porphyry fragments in the Braden tuff that are believed to have been thrown out during the explosive eruption. These intrusions probably constituted a second and higher upsurging of molten and partly molten rock from the same source as that which produced the eruption. That a second explosion

did not result is possibly due to the fact that this intrusion, unlike the first, did not come in contact with cool wet rocks, being preceded by mineralizing solutions, which heated the rocks through which they passed and sealed with ore minerals fractures previously occupied by ground water.

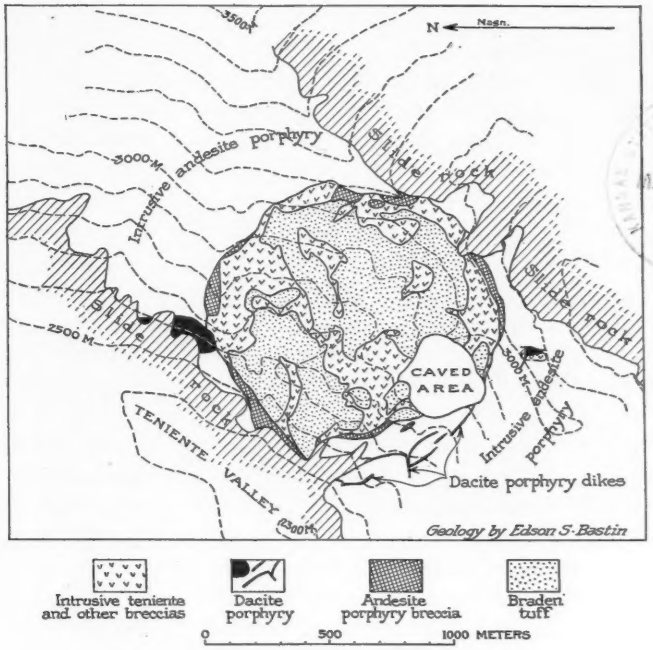

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FIG. 13. Geological map of the Braden Mine, Chile.

The ascending magmas were of two types, one of the composition of dacite and the other of latite, both rich in alkalies and probably related in origin. For the most part these magmas solidified completely before they reached their present position, but continued their upward progress under the pressure of still molten magma below, becoming intimately brecciated by internal

and external friction during the later part of their ascent (Teniente breccia). Some portions of the dacite magma appear to have worked their way upward more rapidly through fissures in the andesite porphyry, reaching their present condition in a molten condition and there solidifying to form the dikes of massive dacite porphyry occurring near the "crater" and the larger body near the portal of Teniente No. 1. (See Fig. 11.) Complete gradations are traceable locally from massive dacite porphyry into Teniente breccia composed wholly or mainly of dacite porphyry fragments. The intrusive origin of the breccia is further indicated by the typically dike-like forms which it locally assumes.

Brecciation of Second Period Ores.—As explained above the Teniente breccias were, in the main, masses of rock fragments forced upward by the pressure of partly molten and molten rocks below. In their upward progress they exerted a considerable friction on the andesite porphyry of the walls of the vent. Although the fractures in that porphyry had been partly sealed by sulphides during the second mineralization, it was still a weak body of rock, and large masses of it were intimately brecciated during the intrusion of the breccia. In this manner were formed the bodies of andesite porphyry breccia which characterize the periphery of the vent, and which normally lie between Teniente breccia and massive andesite porphyry, although in some localities Teniente breccia has been forced between the two into direct contact with massive andesite porphyry, as on the east side of the vent. (See Fig. 13.)

As might be inferred from this mode of formation of the andesite porphyry breccia, no sharp boundary line can usually be drawn between it and the Teniente breccia, yet the mapping of the distribution of the two breccias offers no serious difficulties since the transitions from breccias composed almost wholly of andesite porphyry fragments into breccias carrying only scattered fragments of andesite porphyry commonly takes place in the space of 2 or 3 meters or less. At this stage in the history of

the mine the metal content of both breccias was in pyrite and chalcopyrite contained in fragments; sulphides that were originally deposited along fractures in the andesite porphyry during the main mineralization. The copper content averaged considerably less than 1.5 per cent. The open texture of the breccias was, however, especially favorable to the subsequent enrichment by descending solutions, and by that process large bodies of breccia became converted into ore. In places also their copper content was augmented by sulphides deposited during the third and last period of primary mineralization as will be shown later.

Tourmalinization of the Alkali Breccias.—Originally the matrix of most of the Teniente breccia was composed of small fragments similar in composition to the larger fragments, but shortly after their intrusion borax solutions rising from below partially replaced the matrix of most of these breccias by minute tourmaline crystals producing the gray to nearly black matrix so characteristic of many of these rocks. The solutions producing this change circulated chiefly about the periphery of the vent, and there the tourmalinization was greatest. Along the northwest border of the vent, where there is very little Teniente breccia, the Braden tuff was extensively tourmalinized by the same solutions. Bodies of Teniente breccia in the central portions of the vent well within the Braden tuff were in general little tourmalinized. This tourmalinization was not accompanied by deposition of sulphides.

Third Period of Primary Sulphide Mineralization.—The next event in the geologic history of the mine was renewed mineralization in which the peripheral portion of the filled vent again formed a channel for the upward passage of copper-bearing solutions. These solutions rarely deposited tourmaline, but, on the contrary, dissolved it, locally bleaching the tourmaline-bearing breccias, taking tourmaline into solution and depositing various other minerals in its place. In this respect they contrasted with the tourmalinizing solutions of the main period of primary mineralization and with the solutions of the preceding tourmalinizing period. This poverty in tourmaline probably indicates that

the solutions were not so hot as those that preceded, and it may be inferred that some little time, during which cooling of the rocks was in progress, elapsed between the tourmalinizing of the Teniente breccia and this mineralization.

This third mineralization was much less extensive than the second or main mineralization, but its ores were richer and characterized by a much greater variety of minerals. Most of the spectacular ores of the mine and those first worked by the Spaniards belonged to this period. A few moderate sized bodies of ore were formed, the "bornite" ore body being an example, but many of the ore bodies are too small to be of much value. In places, the copper content of the earlier formed main ore bodies was increased by additions of sulphides at this period.

The sealing of the fractures in the andesite porphyry by sulphides of the second period, and the sealing of the pores of the various breccias by tourmaline resulted in confining the active circulation of the later solutions mainly to scattered zones of fracturing formed since the second mineralization. Open spaces being now comparatively rare, it became necessary for the mineralizing solutions in many places to dissolve tourmaline or rock minerals to provide space for the deposition of sulphides or other ore minerals, a process well understood by students of ore deposits under the name replacement.

The dissolving of tourmaline is particularly well illustrated by the bleaching of the Teniente breccia adjacent to some of the third period ores. The boundaries between bleached and unbleached breccia may be irregular, but are invariably sharp. The microscope shows that the bleaching is caused essentially by the destruction of dark colored tourmaline and the development of the light colored mineral sericite in its place.

The third period of mineralization was characterized by a great variety of minerals not all of which are present in any one locality. In the following list those that occur only rarely or in small amounts are starred:

Sulphides.—Pyrite, FeS_2.
Chalcopyrite, $CuFeS_2$.
Bornite, Cu_5FeS_4.
*Galena, PbS.
*Sphalerite, ZnS.
*Molybdenite, MoS_2.
Arsenosulphides.—Tennantite, $Cu_8Sb_2S_7$.
*Enargite, Cu_3AsS_4.
Carbonates.—Siderite, $FeCO_3$.
Rhodochrosite, $MnCO_3$.
*Calcite, $CaCO_3$.
Oxides.—Quartz, SiO_2.
Sulphates.—Anhydrite, $CaSO_4$.
*Barite, $BaSO_4$.
Tungstates.—*Hubnerite, $MnWO_4$ with a little iron.

Gypsum is secondary after anhydrite. The minerals listed above are present in very different proportions in different parts of the mine; in the bornite ore body, for example, the predominant minerals are bornite, chalcopyrite and siderite; in certain small ore bodies associated with bleached Teniente breccia in the Teniente workings the dominant minerals are chalcopyrite, tennantite and anhydrite.

All of the rock formations of the mine were mineralized in places during this period, and in nearly all some workable ores were developed.

A fourth phase of mineralization may be recognized, during which the temperature was still further lowered. It represents the last dying efforts of the mineralizing solutions. This deposition is local and took place only in open cavities where chalcopyrite and bornite were found in small amounts, together with small crystals of barite and quartz, and wonderfully large crystals of gypsum. One of these caves was open in 1917. It was possible to crawl into it and it contained one large flat lying crystal of gypsum ten feet long and three feet in diameter; there were also many crystals of the same mineral, of lesser size, some

of the size of a fence post, and the cave was more or less coated by small cystals of the minerals referred to in this paragraph.

Other Rock Formations of the Braden Vent.—Two other classes of rocks which should be mentioned for the sake of completeness are granite porphyry breccia and lamprophyre.

The granite porphyry breccia is known only within the "crater." There it forms outcrops conspicuous for their light greenish gray color which contrasts strongly with the brownish color of the Braden tuff with which the breccia is usually associated. It has not been cut in any of the underground workings.

The granite porphyry breccia is similar in origin to the Teniente breccia. It crystallized at greater depths than those at which it is now found, and during or immediately after crystallization was forced upward into its present position by the pressure of still molten or partly molten granitic material below, becoming brecciated by friction, internal and external, during its upward progress.

The granite porphyry breccia is younger than the period of tourmalinization that followed the intrusion of the Teniente breccia, and with the exception of the single dike of lamprophyre is the youngest formation of the crater. It is probably older than the third or last period of primary mineralization, as is indicated by the presence of small amounts of sulphides.

The lamprophyre occurs as a single dike about 2 meters in average width exposed on the surface on the southwest side of the crater near the divide between Teniente valley and Canyon Diablo, and exposed underground in the Regimento workings.

The lamprophyre appears to be the youngest rock of the district and is entirely unmineralized.

Erosion and Chalcocite Enrichment.—In the further history of the Braden mine, tilting and uplift of the land, erosion of the surface by streams and the action of the air and surface waters upon the ores assumed the leading rôles. At some period, not definitely known but subsequent to all the events that have been described, the whole region about the Braden mine was tilted

and probably also uplifted, so that the volcanic rocks of the Cerro Negro series and the Braden tuffs, deposited in a nearly horizontal position, assumed their present attitude with gentle dips of 15 to 20 degrees to the southeast. (See Fig. 13.)

At this time there were present around the periphery of the old vent large bodies of rock mineralized to the extent of approximately 1 to 1.25 per cent. copper, and a few small bodies much more highly mineralized. Further mineralization was necessary to form large bodies of workable ore, and this mineralization was accomplished by the action of the air and of surface waters on the primary ore—the process commonly known as secondary enrichment, or downward enrichment. From the close of the last period of primary mineralization to the present day the country about the "crater" has been continuously subjected to gradual wearing down of the surface through the fracturing and disintegration of the rocks by temperature changes and by snow and ice. Glaciers and streams carried away the debris. As soon as these processes had brought the surface down to the copper-bearing rocks, the combined action of the air and of waters of surface origin led to the oxidation of the copper-bearing sulphides and the taking into solution, mainly as copper sulphate, of much of the copper. Some of the copper remained in the near-surface oxidized zone as cuprite, chrysocolla, and other oxidized copper minerals; but much of it was carried downward in solution and redeposited as chalcocite where these solutions came in contact with primary pyrite and chalcopyrite, the latter being always more easily replaced. The chalcocite replaced the chalcopyrite and pyrite volume for volume, and since it carries approximately 80 per cent. of copper as against 34.5 per cent. in chalcopyrite and none in pyrite, the process resulted in notable enrichment, bringing the large bodies of 1 to 1.25 per cent. material formed during the main primary mineralization up to 1.5 to 4 per cent. or even higher in copper and rendering them commercially workable.

Chalcocite enrichment is observable immediately below the

heavily leached capping of the ore bodies. Downward, its extent is greatest under the ridge on the east side of the crater and least under Teniente Creek. Its downward limit, determined for the most part by actual observation, exhibits considerable regularity. In other regions, where chalcocite enrichment has been studied, the distribution of chalcocite bears a very definite relation to the ground water level; it is probable that at the Braden mine the form of the enrichment surface is related to that of a former ground water level.

In many mountain regions, and especially in those where massive igneous rocks are abundant, the ground water circulation is restricted to scattered fracture zones, and the level at which the ground water stands in one fracture may be quite independent of its height in another unless the two happen to be laterally connected. In such regions, a general ground water level can hardly be said to exist. Conditions of this sort probably obtain in much of the country about the Braden mine, but in the mine itself special conditions favor the existence of a well-defined ground water level. The workings of the Braden mine follow the shattered periphery of a volcanic vent where the rocks are breccias and intimately fractured andesite porphyry. In spite of partial sealing of the seams and irregular openings of these rocks by sulphides or by tourmaline, there was undoubtedly ample opportunity for the ground water to move not only downward, but also laterally parallel to the periphery of the vent, so that there probably existed before mining operations began a fairly regular and definite level below which the openings in the rocks were saturated with water, a level which, of course, fluctuated somewhat with the seasons.

Mining development has drained most of the mine to below the original water level, and the best evidence now available as to the original position of this level is afforded by the lower limit of oxidation. Since oxidation cannot easily go on below the permanent ground water level, the lower limit of oxidation coincides approximately with the ground water level. Making due allowance for oxidation that has occurred since the mine was

opened, it is found to extend locally almost, if not quite, to the lower limit of chalcocite enrichment, a condition which, as pointed out below, is abnormal.

Study of many copper deposits where chalcocite enrichment has occurred has shown that under normal conditions the chalcocite zone extends from shortly above the ground water level to several hundred feet below it. The position of the chalcocite zone at the Braden mine, almost wholly above the ground water level, is believed, therefore, to be abnormal, and the result of moderate uplift since most of the chalcocite enrichment took place. Just before this uplift the ground water level probably stood 100 to 200 and in places even 250 meters above its present position.

Evidences of geologically recent uplift are not confined to the ores, but are found in the topography as well. Flanking the Coya valley at intervals between Caletones and Coya are elevated benches or terraces, remnants of extensive flats which bordered the Coya at a time when many of the hill slopes were less steep than today and the streams less rapid. Rapid uplift increased the gradient of the Coya and caused it to cut a steep narrow valley, in places a veritable canyon, below the level of the flats on which it formerly flowed. In the upper Coya and Teniente valleys, where no flats had been developed, the effect of the uplift was merely to stimulate the streams to more active erosion.

As indicated in a following section, the distribution of the leached and oxidized ores of the mine is also indicative of uplift.

Chalcocite is the only secondary copper sulphide present in important amounts in the zone of chalcocite enrichment, although covellite and bornite were noted. The development of chalcocite is greatest in the upper part of the enriched zone and gradually decreases in depth. In the upper part of the zone, chalcopyrite has, in a few places, been almost completely replaced by chalcocite, and pyrite replaced to a lesser degree; commonly only a thin outer layer of the pyrite is affected. In the lower part of the zone, chalcocite commonly forms thin films along every fracture, however small, in the chalcopyrite, but pyrite is unaffected.

Secondary minerals that appear to have been deposited contemporaneously with chalcocite are covellite, bornite, kaolin and rarely colloidal silica. Secondary bornite is very rare and was noted only in the Teniente breccia where it replaced small chalcopyrite fragments; nearly all of the bornite of the mine is a primary mineral of the third period. Kaolin is locally abundant in the upper and middle parts of the chalcocite zone where it has filled what were small open spaces in the ores. Commonly it has absorbed copper sulphate from the enriching solutions, and is pale greenish rather than white.

The main ore bodies appear to be practically limited below by the lower limit of chalcocite enrichment. All workable ore bodies that have been found below the zone of enrichment are small and are primary ores of the third period.

Oxidation.—While both oxidation and reduction may go on within the oxidized zone the net result of all the chemical changes within it is a great increase in the oxygen content of the ores. The oxidized zone may be looked upon as the complement of the chalcocite zone, for the enrichment in the latter is accomplished at the expense of the impoverishment in copper of the former. All of the copper represented by the chalcocite of the chalcocite zone did not, however, come from the *present* oxidized zone; much of it came from higher up, from oxidized material that has since been eroded.

The oxidized portions of the ore bodies are characteristically rusty in appearance, and softer and less coherent than the sulphide ores. The characteristic minerals are the following, those found only in a few places or in small amounts being starred:

Oxides.—Limonite and possibly other hydrous oxides of iron.
Cuprite, Cu_2O.
*Tenorite, CuO.
Carbonates.—Azurite, $Cu_3(OH)_2(CO_3)_2$.
Malachite, $Cu_2(OH)_2CO_3$.
Silicates.—Kaolin, hydrous silicate of aluminum.

Sulphates.—Chalcanthite, $CuSO_4 + 5H_2O$.
Melanterite, $FeSO_4 + 7H_2O$.
*Spangolite, Basic aluminous sulphate of copper.
Gypsum, $CaSO_4 + 2H_2O$.
*Epsomite, $MgSO_4 + 7H_2O$.

Amorphous Minerals Variable in Composition.

Chrysocolla. Has the composition of a hydrous silicate of copper.

Copper Pitch Ore. Essentially iron-bearing chrysocolla.

A translucent to transparent sky blue mineral having the composition of a basic aluminous sulphate of copper.

Cuprite is commonly a replacement of chalcocite; it is rarely formed in masses more than a few centimeters across. Azurite and malachite are not abundant minerals and are found mainly as alteration products of carbonate-bearing primary ores of the third period. Chrysocolla, the principal green copper mineral of the mine, occurs mainly as thin coatings on the rocks and ore minerals, but is occasionally found in masses several centimeters across, usually filling irregular cavities in association with copper pitch ore.

The ore bodies of the Braden mine are commonly heavily oxidized and leached of a large share of their copper to depths of from 50 to 100 meters. An important characteristic of the oxidation is its local extension downward in tooth-like form to much greater depths than those indicated above. The largest of these areas of deep oxidation lies beneath one of the principal minor valleys excavated in the volcanic vent.

In most of the workings which expose highly oxidized materials there are very abrupt transitions from highly leached material with a copper content of less than 1.5 per cent. or even less than 0.5 per cent. to ores rich in sulphides and assaying over 2.5 per cent. and in places over 3.5 per cent. copper. These are

in some places concomitant with the passage from breccias to massive rock, or from one kind of breccia to another, and in such places are clearly influenced by marked differences in the perveousness of the various formations to the air and oxidizing waters. In other places, transitions equally abrupt take place wholly within massive andesite porphyry and are not accompanied by conspicuous differences in porosity. In the latter cases, especially, the abrupt transitions without the intervention of zones rich in oxidized copper minerals, and the deep extension of "teeth" of oxidized material to the very bottom of the zone of chalcocite enrichment, is indicative of the downward progress of oxidation at a more rapid rate than chalcocite enrichment. The phenomena of oxidation, therefore, as well as the topographic features, and the relation of the lower limit of chalcocite enrichment to the ground water level all agree in indicating that the region in which the mine is located has undergone comparatively recent uplift. The uplift acted as a stimulus to erosion by increasing the grade of the streams; it stimulated oxidation by increasing the distance between the surface and the ground water level and thus exposing new thicknesses of material to oxidation; it also stimulated chalcocite enrichment, but as this is a slow process the downward movement of the chalcocite zone since the uplift has been slight. The oxidized zone has come as a consequence to overlap the zone of chalcocite enrichment instead of lying uniformly above it, and "teeth" of highly leached and oxidized material have come to penetrate nearly to the bottom of the chalcocite zone between walls of rich and little oxidized chalcocite ore.

THE MINING OPERATIONS.

This is not the place to describe the methods of mining and smelting adopted at the Braden mine, but a few statements will serve to impress the reader with the magnitude of the operations.

From the Annual Report of the Braden Copper Company for 1920, we abstract the following statements:

According to Mr. Fred. Hellmann, Consulting Mining Engineer

of the Company, the ore reserves consist of 176,640,000 net tons of positive ore of an average grade of 2.45 per cent. copper, and 87,570,000 net tons of probable ore of an average grade of 1.87 per cent. copper. During 1920, the daily average of dry ore treated was 6,025 tons, containing 2.078 per cent. of copper. Blister copper was recovered amounting to 32,459 tons, indicating an average extraction of 71.73 per cent.

The ore is mined by a highly developed caving system and carried down to the main transportation level through an elaborate system of ore passes.

Concentration is effected at Sewell, about a mile below the mine, by jigs and tables followed by flotation process. The mill recovery is about 80 per cent. The concentrates are smelted to blister copper at the same place. Future plans include the raising of the daily output of ore to 10,000 tons.

The electric power is furnished by the extensive Cachapoal Power system, installed by the company.

PHOSPHORUS IN CALIFORNIAN PETROLEUM.

CHASE PALMER.

Operators in oil fields already realize the importance of knowing something of the composition of underground waters, but the general impression seems to be that nothing more is needed than a statement of the items employed to determine the fitness of a water for use in a steam boiler. Consideration of the composition of oil field waters is confined almost wholly to the major constituents of such soluble minerals as common salt, glauber's salt, gypsum and soda. Little evidence concerning the minor constituents of oil field solutions has been sought and it is not surprising, therefore, that in the waters of the oil measures of California phosphates have escaped observation. If the prevailing opinion is correct, namely, that phosphates in all waters are derived only from the mineral, calcium phosphate, dissolved with difficulty out of the adjacent rocks and sands, then, of course, the minute quantity of phosphate possible in an oil field solution can have little significance and may well be disregarded. If, on the other hand, phosphorus can be found in the oil with which these subterranean solutions have been in contact, then the importance of knowing the phosphate content of an oil field water is apparent.

On a single section of the Sunset district, California, five well waters presumably from the same oil sands were found to contain phosphates in quantities ranging from 0.4 to 2.6 parts of phosphates (PO_4) in one million parts of solution. Although all of these solutions are primarily brines, some of them are modified chiefly by interaction with oil while others are mixtures containing also waters intruding from outside the oil measures. The persistence of phosphate in these waters suggested the possibility that phosphorus might also be present in the oil of that locality. Consequently a heavy oil from the same section that produces the phosphate solutions was closely examined and

found to contain phosphorus to the amount of one one-hundredth of one per cent. of its weight. Another heavy oil drawn from a shallow well in the Kern River oil field also showed a phosphorus content of one one-hundredth of one per cent. This well has been producing oil for several years.

NITROGEN COMPOUNDS IN CALIFORNIAN PETROLEUM.

Phosphorus and nitrogen in the properties of their compounds resemble each other closely and since nitrogen compounds constitute a large part of a Californian crude oil, consideration of the chemical nature of these nitrogen compounds may throw light on the source of phosphates in oil field solutions.

Californian petroleums consist essentially of three very different classes of organic compounds, namely, hydrocarbons, hydrocarbons with sulphur, and hydrocarbons with nitrogen. The nitrogenous hydrocarbons are usually called organic nitrogen bases. Members of all of these classes are oxidizable, but their oily nature shields them from direct attack of inorganic oxidants mobile in the waters or fixed in the rocks. The organic nitrogen bases, however, form soluble salts with strong acids so that considerable quantities of these nitrogen bases are undoubtedly dissolved by the corrosive waters of the oil measures and the resulting solutions of organic nitrogen salts, necessarily in a state of high dilution, can offer little resistance to the attacks of oxidants. In 1899 Mabery[1] prepared a long series of organic nitrogen bases by distilling an oil from Santa Paula, California. More recently Mabery and Wesson[2] have shown that under certain conditions an inorganic oxidant, like potassium permanganate, oxidizes these organic nitrogen bases to organic nitrogen acids, while under other conditions ammonia is formed. Appreciable amounts of ammoniacal compounds and of organic nitrogen acids are therefore to be expected in a water closely

[1] Mabery, C. F., *Journ. Soc. Chem. Ind.*, vol. 19, 505 (1900).

[2] Mabery, C. F. and Wesson, L. G., "Constitution of the Organic Nitrogen Bases of California Petroleum," *Amer. Chem. Soc. Journ.*, vol. 22, 1014 (1920).

associated with a Californian oil. The organic acids obtained by Mabery are derivatives of pyridine, an important constituent of bone oil produced by distilling the bones of vertebrates.

NITROGEN COMPOUNDS AND PHOSPHATES IN OIL FIELD WATERS.

Waters from the oil measures of the Sunset, Midway, Kern River and Coalinga fields were found to contain nitrogen compounds in the forms of free ammonium salts and of organic nitrogen acids, often in large amounts. These products conform to the products which Mabery and Wesson obtained by oxidizing the organic nitrogen bases extracted from the oil from Santa Paula. Nitrogen compounds were not looked for in every water in which phosphate was known to be present, but whenever nitrogen compounds were sought in phosphate waters they were found.

A well that has been producing both oil and water in the Sunset district furnishes strong evidence that the oil has suffered powerful mineral oxidation. The water solution brought up with the oil and primarily a brine, itself somewhat modified by the mineral material which it has dissolved out of the rocks, was found also to contain free ammoniacal compounds as well as organic nitrogen compounds in amounts corresponding to 335 parts of ammonium chloride and 1,635 parts of organic nitrogen acids in one million parts of the solution. This water also contained 2.7 parts of phosphate per million.

The presence of phosphorus in Californian oils and the usual association of phosphates with the soluble oxidation products of organic nitrogen bases in the waters of the oil measures point to the oil as the source of these phosphates.

UNDERGROUND OXIDATION.

When nitrogenous organic matter decays under atmospheric conditions nitrites and nitrates are among the final oxidation products and surface waters polluted by decomposing organic matter often contain nitrogen in all the four forms that have been mentioned. It is a striking fact that these aqueous solu-

tions brought up by the wells, solutions which have reacted with the oils underground and are charged with ammoniacal salts and organic nitrogen acids, have failed to show the presence of nitrates and nitrites. The organic nitrogen bases of the petroleum, therefore, normally suffer only partial oxidation underground, the limit of oxidation coinciding with the limit which Mabery and Wesson reached by oxidizing the organic nitrogen bases of Santa Paula oil with potassium permanganate.

Manganese dioxide and other higher oxides of manganese are freely distributed in the oil regions of California. With corrosive brines they would form soluble manganous chloride and halogen which by a cycle of well-known reactions easily produces active oxygen from the solution. Oil field solutions usually contain manganous chloride formed probably by the reduction of a manganic oxide by the organic nitrogen salts dissolved from the oil. Moreover, higher oxides of manganese seem to be easily accessible because the muds brought up with the oil and water often contain the dark oxides of manganese.

VENTURA EMULSION.

To learn whether the dual occurrence of phosphorus in oils and waters is peculiar to the oil measures of San Joaquin Valley examination was made of an emulsion[3] from the Ventura oil field close to the Pacific coast and about fourteen miles distant from Santa Paula. The permanent emulsion still contained 53 per cent. of suspended water and about 0.005 per cent. of mineral material that could not be removed. Manganese was found in this residue which had been held up in the emulsion.

The oil in this emulsion was found to contain phosphorus to the amount of 0.008 per cent. of its weight.

The water set free from the emulsion is a brine containing free ammonium salts and organic nitrogen compounds in abundance. A very small quantity of soluble manganous salt is also present. The water was perfectly free from nitrites and nitrates, but it contained as much as 5.2 parts of phosphate per million. The

[3] Supplied by Mr. B. H. van der Linden of the Shell Oil Company.

activities in the Ventura oil measures are evidently like the activities in the oil measures of San Joaquin Valley.

The conclusions reached in this investigation are briefly stated in the following summary.

SUMMARY.

Californian heavy oils containing nitrogen bases have been found also to contain phosphorus.

These nitrogen compounds and phosphorus compounds may be oxidized by minerals through the agency of underground water solutions and without the help of atmospheric oxygen.

The association of phosphorus compounds with nitrogen compounds in oils of different fields is another link in the chain of evidence that Californian petroleum is of animal origin.

EATON LABORATORIES,
SAN FRANCISCO.

ON THE METASOMATIC PROCESSES IN SILICATE ROCKS.[1]

V. M. GOLDSCHMIDT.

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INTRODUCTION.

Definition.—The term metasomatism, as originally defined by C. F. Naumann, was applied to certain kinds of pseudomorphs, namely, those formed by chemical replacement at the expense of some original mineral. Every transformation of minerals by chemical replacement would be designated as metasomatism, and in this sense, most of the newly formed constituents of the metamorphic rocks would be metasomatic minerals.

Later, however, the conception of metasomatism was narrowed, and was used to comprise those transformations only by which the chemical composition of the whole rock, as well as that of the individual minerals, was essentially changed. Meta-

[1] Manuscript originally transmitted in German and translated by P. Eskola, P. Armstrong, and the Editor.

somatism in this sense would include, for example, the alteration of limestone into dolomite.

The definition of metasomatism as a transformation of a rock with essential changes in its composition is not quite satisfactory either. The transformation of a calcareous sandstone, for instance, into a wollastonite rock by contact metamorphism, whereby carbon dioxide is driven off, is not called metasomatism, in spite of the fact that the composition of the rock is essentially changed through the loss of carbon dioxide. Rather is it customary to apply the term metasomatism especially to those processes which involve an addition of substances into the rock.

We shall base our discussion on the following definition of the term metasomatism:

"Metasomatism is a process of alteration which involves enrichment of the rock by new substances brought in from the outside. Such enrichment takes place by definite chemical reactions between the original minerals and the enriching substances."

According to such a definition the processes of mere impregnation are excluded from the conception of metasomatism. The newly introduced substances may take the form of either gases, aqueous solutions or melts, and their reactions with the original constituents of the rock result in the formation of metasomatic and possible accessory minerals.

Importance.—If no metasomatic replacement accompanied metamorphism, the chemical composition of the metamorphosed rock would not change, except for a possible loss of volatile compounds and subtraction or addition of substances by the ordinary processes of leaching and impregnation. Then, Rosenbusch's rule of the constancy of chemical composition in metamorphism would be valid almost without exception.

The effect of metasomatism, however, introduces many exceptions to this rule. Such processes at first were described particularly only in carbonate rocks, although silicate rocks have also furnished a number of similar examples, as Lindgren has emphasized in his descriptions of the geology of certain ore deposits. Recently others, especially P. Eskola, have called attention to the

important influence of various metasomatic processes in silicate rocks. As examples of such replacements, connected with ore deposits, may be mentioned the formation of greisen, scapolite, and magnesium-silicate rocks. For two reasons, such phenomena have been studied chiefly in the vicinity of ore deposits. In the first place, many ore deposits and the regions surrounding them have been the scene of exceptionally intense chemical replacements, partly simultaneous with ore deposition, partly succeeding it. Secondly, the economic importance of ore deposits often calls for detailed chemical and microscopical study of both the deposits and the country rocks.

A critical review of the literature, however, shows that replacement is not necessarily associated with the formation of ore deposits only, but that various metasomatic processes of greatly differing character may also accompany rock metamorphism. A great number of rocks owe their present character to metasomatic replacement, and should be considered in a class by themselves. They are as justly entitled to a separate classification as are rocks of igneous and sedimentary origin, or those formed by "normal" metamorphism, *i.e.*, metamorphism without addition of substances. A distinction should be made, therefore, between the two kinds of metamorphic rocks in the petrographic system:

1. Products of "normal" metamorphism where the chemical composition of the original rock has remained unaltered.

2. Products of metasomatic metamorphism which owe their present composition essentially to the introduction of new substances.

In my report on contact-metamorphism in the Christiania region,[1] I pointed to the existence of these two different types of contact rocks, and I believe that a similar division might prove useful in the case of the crystalline schists. We are not justified in diagnosing the origin of a metamorphic rock from its present chemical composition; attempts to do so have led to many faulty conclusions. In illustration, I may mention that not all antho-

[1] V. M. Goldschmidt, "Die Kontaktmetamorphose im Kristiania-Gebiete," *Vid. Selsk. Skr. Mat.-Naturv. Kl.*, 1911, No. 1.

phyllite schists are metamorphosed igneous magnesium-silicate rocks. In most cases, they were derived from quartzites and other highly siliceous rocks acted upon by magnesia-bearing solutions. Again, nearly all andradite rocks are metasomatic derivatives from limestones, and many gneisses of granitoid composition owe their existence to the metasomatic feldspathization of argillaceous rocks.

We may mention still another circumstance pointing to the common occurrence of metasomatic processes in rock metamorphism, namely, that crystalline schists have, in very numerous cases, been explained as derivatives of tuffs. If all these interpretations were true, tuffs would be far commoner within metamorphosed formations than they are among non-metamorphic rocks. Apparently, in many cases, the chemical composition of metasomatic rocks, lacking marked igneous as well as marked sedimentary characters, has been regarded as a proof of tuffaceous origin, and the possibility of metasomatic changes has not been considered.

CLASSIFICATION OF METASOMATIC PROCESSES.

No detailed classification of metasomatic processes has heretofore been attempted, although a preliminary one dealing with metasomatism in silicate rocks was recently published by the writer,[2] and in a later publication somewhat elaborated upon.[3] The purpose of the present paper is an attempt at a classification of metasomatic processes as affecting silicate and silica rocks, examples being given in each case.

Generally, metasomatic processes may be considered under four main headings, based on the character of the rock involved:

Metasomatism of silicate and silica rocks.
Metasomatism of carbonate rocks.
Metasomatism of salt deposits.
Metasomatism of sulphide deposits.

[2] V. M. Goldschmidt, "Geol.-petrogr. Studien im Hochgebirge d. Südl. Norwegens V., Die Injektionsmetamorphose im Stavanger-Gebiete," *Vid. Selsk. Skr. Mat.-Naturv. Kl.*, 1920, No. 10, 1921.

[3] V. M. Goldschmidt, *Geol. Fören. i Stockholm Förh.*, vol. 43, p. 463, 1921.

The first group is exemplified by the scapolitization of a plagioclase rock, or the formation of anthophyllite at the expense of quartz, the second by the alteration of limestone into siderite, or andradite. As illustrative of the third group may be quoted the change of anhydrite into polyhalite, or glauberite, while various kinds of alteration in the zone of cementation in sulphidic ore deposits typify the fourth group.

Besides these four principal kinds of metasomatism, some others of lesser importance may be mentioned, as, for example, the metasomatism of oxidic rocks, and that of certain coals by enrichment in vanadium.

In discussing each main group, further subdivisions are needed and these may advantageously be based upon the character of the added substances. The first group, which alone of the four mentioned will be discussed in the present paper, may then be considered under two sub-headings:

(*a*) Metasomatism of silicate rocks with addition of metal compounds.

(*b*) Metasomatism of silicate rocks with addition of metalloids or compounds of metalloids.

METASOMATISM OF SILICATE ROCKS WITH ADDITION OF METAL COMPOUNDS.

According to the metal introduced, we may further differentiate between alkali-, magnesia-, lime-metasomatism and others.

Alkali Metasomatism.—Alkali metasomatism is decidedly common in silicate rocks. A reason for this, probably, is to be found in the comparatively high solubility of most alkali compounds, excepting the complex alkaline silicates of alumina and iron. Hence the latter represent the newly formed metasomatic minerals.

The various chemical processes arising in alkali metasomatism and resulting in the binding of the alkalies may be treated specifically as:

A. Metasomatic exchange of the alkalies.
Examples: Formation of myrmekite or "chess-board albite" from potash feldspar.
Formation of adularia from plagioclase (in propylites).
Formation of muscovite from nephelite.

B. Binding of alkali by excess alumina in the precipitating mineral.
Examples: Metasomatic formation of feldspar in the contact zones of injected rocks.
Metasomatic formation of feldspar in the inclusions of hornfels.
Metasomatic formation of feldspar in pyro-metamorphic rocks.

C. Binding of alkali by silicates of Mg, Fe″ and Fe‴.
Examples: Formation of biotite in amphibolites in contact zones.
Formation of ægirite in certain contact zones.

D. Binding of alkali (and alumina) by quartz.
Examples: "Syenitization" of granite in certain contact zones of alkaline rocks.

The two examples quoted under *A*, namely, the formation of myrmekite or "chess-board albite" at the expense of potash feldspar[4] and that of adularia from plagioclase,[5] show quite clearly that the direction, chemically speaking, of metasomatic replacement is not necessarily always the same, but may vary with the concentration of the solutions added and with the temperature and pressure prevailing during the reaction. Such "reversible" replacement has been observed in quite a few pseudomorphs of minerals.

A common case is that mentioned under *B*, namely, the metasomatic formation of feldspar at the expense of minerals and rocks containing "excess alumina," *i.e.*, of those in which $Al_2O_3 : Na_2O + K_2O > I$. A series of similar occurrences

[4] F. Becke, "Denkschriften d. k. Akad. d. Wissensch." *Wien. Math.-Naturw. Kl.*, I., Bd. 75, I. Halbbd., 1913.

[5] W. Lindgren, "Mineral Deposits," p. 469, London and New York, 1919.

has been described by the writer and others.[6] The formation of adinoles in shales along contact zones of diabases may be considered as belonging to the same group.

Of similar character, evidently, is the replacement of lime by soda in lime-bearing plagioclases, described by P. Geijer[7] and N. Sundius[8] from the Kiruna district. Such change results in albitization of the plagioclase with addition of soda, as distinguished from common saussuritization which takes place without any change in total composition of the affected mineral. Quite possibly, also, many glaucophane rocks may owe their present chemical composition to metasomatic addition of soda.

Not less common is case *C* where alkali is bound by the iron-magnesium minerals of the original rock. The formation of biotite at the expense of amphibole, described by Becke,[9] and the formation in contact rocks of ægirite by metasomatic addition of soda, described by the writer,[10] are examples of this case.

Case *D*, the formation of feldspars from quartz by addition of alkalies and alumina which are brought in either as dissolved alkali aluminates or as nephelite in solution, apparently is common in the contact zones around ijolites and related abyssal rocks rich in nephelite. It changes granites into syenitic rocks. An example which my colleague, Professor W. C. Brögger, and I had

[6] V. M. Goldschmidt, "Die Kontaktmetamorphose im Kristiania-Gebiete." Die Injektionsmetamorphose im Stavanger-Gebiete."

E. Becke, "Denkschriften d. k. Akad. d. Wissensch.," *Wien. Math.-Naturw. Kl.*, I., Bd. 75, I. Halbbd., 1913. "Typen der Metamorphose," *Geol. Fören. i Stockholm Förh.*, Bd. 42, p. 183, 1920.

R. Brauns, "Uber Laacher Trachyt und Sandinit," *Sitzungsber. d. Niederrhein. Ges. f. Nat.- u. Heilkunde*, Bonn, 1911. "Die Kristallinen Schiefer des Laacher Seegebietes und ihre Umbildung zu Sandidinit," Stuttgart, 1911. "Die chemische Zusammensetzung granatführender krist. Schiefer u. s. w. aus dem Laacher Seegebiete," *N. Jahrb. f. Min.*, Beil.-Bd. XXXIV., p. 85, 1912.

[7] P. Geijer, "Geology of the Kiruna District 2." Stockholm, 1910.

[8] N. Sundius, "Beiträge zur Geologie d. südlichen Teils d. Kiruna-Gebietes," Uppsala, 1915. "Zur Frage der Albitisierung im Kiruna-Gebiete," *Geol. Fören. i Stockholm Förh.*, Bd. 38, p. 446, 1916.

[9] F. Becke, *Geol. Fören. i Stockholm Förh.*, Bd. 42, p. 183, 1920.

[10] V. M. Goldschmidt, "Uber einen Fall von Natronzufuhr bei Kontaktmetamorphose," *N. Jahrb. f. Min.*, Bd. XXXIX., p. 193, 1914.

the opportunity of studying very closely has been described recently by the former[11] from the Fen Area, in Telemark, Norway, as "Fenite," from Archæan granites in the contact zones of alkaline rocks.

Magnesia Metasomatism.—Magnesia is bound by quartz or acid silicates forming anthophyllite or cordierite. The magnesium-silicate rocks occurring in many contact zones of granites afford an example.

Metasomatism of this kind was first described by P. Eskola in his report on the petrology of the Orijärvi region in Finland.[12] Analogous phenomena were recorded by P. Geijer from the Falun region and other districts in Sweden.[13] Peculiar, and apparently characteristic, is the association of these metasomatic magnesium-silicate rocks with sulphidic ore deposits. From his study of the Orijärvi region and Geijer's investigations of the ore deposits of Falun, Eskola was led to emphasize the great general importance of metasomatism in silicate rocks.

The widespread existence of magnesium compounds in circulating solutions is illustrated by the well-known process of dolomitization of limestones. In connection with magnesia metasomatism, it may be mentioned that aqueous solutions of magnesium salts are capable of dissolving considerable amounts of silica. Analysts have long been aware of this fact, while I have been able to ascertain experimentally that, when olivine is decomposed by dilute acids, a large part of the silica goes into solution.

Lime Metasomatism.—Lime is bound by excessive alumina, as

[11] W. C. Brögger, "Die Eruptivgest. d. Kristianiagebietes, IV., Das Fengebiet in Telemark," *Vid. Selsk. Skr. Mat.-Naturv. Kl.*, 1920, No. 9. pp. 150–167, 1921.

[12] P. Eskola, "On the Petrology of the Orijärvi Region in Southwestern Finland," *Bull. Comm. géol., Finl.*, No. 40, 1914. "Om sambandet mellan kemisk och mineralogisk sammansättning hos Orijärvitraktens metamorfa bergarter," *Bull. Comm. géol. Finl.*, No. 44, 1915. "Om metasomatiska Omvandlingar i silikatbergarter," *Norsk geologisk tidskrift*, Bd. VI., p. 89, 1921.

[13] P. Geijer, "Falutraktens berggrund och malmfyndigheter," *Sveriges geol. Undersökn.*, serie C, No. 275, 1917. "Recent Work on the Sulphide Ores in Fenno-Scandia," Economic Geology, vol. 16. p. 279, 1921.

shown by the formation of epidote at the expense of micas. Similar examples of this metasomatic process have been given by the writer from the injection contact-zones of the Stavanger region.[14]

A combined lime-magnesia metasomatism may also occur, giving rise to amphibole or pyroxene at the expense of quartz and lime- and magnesia-bearing solutions. To this group probably belongs the malacolite rock of Skutterud in Norway, to which my colleague, Professor J. Schetelig, called my attention.

Iron Metasomatism.—(*A*) Dissolved iron salts are precipitated by silicates, or quartz, as iron silicates.

(*B*) Dissolved iron salts interact with silicates forming iron oxides or hydroxides.

This kind of metasomatism apparently is represented by those replacements which have changed diabases, greenstones and slates into iron ores. It is possible that many cases thought to belong to this group should properly be referred to replacements of either primary or transitionally formed carbonates.

An example of case *A*, recently described by Sundius,[15] is the metasomatic formation of biotite and almandite at the expense of alkali feldspar. Cases of metasomatic formation of manganese formations, analogous to those of iron, are also known.[16]

Nickel Metasomatism.—Dissolved nickel salts are precipitated by serpentinous silicates as garnierite. Presumably, many garnierite deposits have originated in this manner.

Still other kinds of enrichment in heavy metals might possibly be classed as silicate metasomatism, for example, the precipitation of native metals such as gold, silver, or copper by ferrous silicates. In this case, however, it is the reducing ferrous iron content of the latter, rather than the silicates themselves, which controls the direction in which the chemical reaction proceeds.

[14] V. M. Goldschmidt, "Die Injektionsmetamorphose im Stavanger-Gebiete."

[15] N. Sundius, "Åtvidabergstraktens geologi och malmfyndigheter," *Sveriges Geol. Undersökning,* serie C, No. 306, 1921.

[16] Beyschlag-Krusch-Vogt, "Die Lagerstätten der nutzbaren Mineralien und Erze," 3, Bd. II., p. 348.

The copper deposits of the Lake Superior type well illustrate this case.

In this connection also might be mentioned the deposition of cinnabar in sandstones and quartzites, probably according to the following reaction: Alkaline solutions of alkali-mercury sulphosalts react with quartz forming alkali silicates and mercury sulphide, the latter separating in solid form.

METASOMATISM IN SILICATE ROCKS OF METALLOIDS OR THEIR COMPOUNDS.

Among the processes of silicate metasomatism with addition of metalloids or compounds of metalloids, we may again discriminate, according to the substances brought in, between halogen-, sulphur-, phosphorus-metasomatism, and others. The following mode of grouping seems to be appropriate:

Fluorine-Chlorine-Boron Metasomatism.—(*A*) Fluorine or boron (or both) are bound by excess alumina.

Examples: Formation of topaz in hornfels. Formation of tourmaline in hornfels.

(*B*) Chlorine or fluorine (and water) are bound by feldspars.

Examples: Formation of scapolite at the expense of feldspars. Formation of greisen in pneumatolytic tin deposits and by analogous pneumatolytic or hydrothermal processes.

In case *A*, it is noteworthy that topaz and tourmaline seem to form preferably in rocks containing an excess of alumina, especially in slates.[17] When, however, these two minerals are found as metasomatic products in feldspar rocks without an original content of excess alumina, we may suspect that micas carrying excessive alumina had been formed as transitional products.

Case *B*, as well as *A*, is of widespread occurrence. The formation of scapolite at the expense of feldspars, especially of plagioclase, takes place under varying geological conditions. It may attain regional distribution, as described by Sundius from

[17] H. Rosenbusch, "Physiographie der massigen Gesteine," Bd. II., i, pp. 124–126, 1907.

the Kiruna district,[18] it may be limited to contact zones, as observed by the writer in the Christiania region,[19] or it may occur in the immediate vicinity of apatite veins, as those of southern Norway.

As is well known, greisen is generally associated with tin veins and related mineral deposits, and more or less gradually merges into rocks containing sericite, formed by hydrothermal alteration of the feldspars. The formation of typical greisen is frequently accompanied by the addition of lithia, a process apparently related to the metasomatic exchange of alkalies.

Sulphur Metasomatism.—(*A*) Formation of sulphides at the expense of iron-bearing silicates.

Example: Impregnation of rocks, originally iron-bearing, with pyrite and pyrrhotite in many contact zones.

(*B*) Sulphatization of feldspars and feldspathoids.

Example: Formation of alum-rock by volcanic exhalations.

An example of case *A* is afforded by "impregnation" deposits of pyrite in slates near intrusive rocks, recently described by Vogt[20] as of metasomatic origin. He believes them to have been formed by reactions between chlorite or biotite rich in iron, and hydrogen sulphide. To this class belong certain sulphide minerals which were formed by reduction of sulphates by ferrous silicates, for example, the impregnation of basic lavas with chalcocite as observed in many contact zones of the Christiania region. This case is analogous to the precipitation of native metals by ferrous silicates.

Case *B* is common in volcanic districts. Here, the active substances apparently were SO_2 and SO_3, while in most cases water vapor or water was probably also present.

Water and Carbon Dioxide Metasomatism.—Water and carbon dioxide are bound either during diaphthoresis or weathering, often with simultaneous leaching of primary constituents from the silicates.

[18] N. Sundius, "Beiträge zur Geologie d. südl. Teils d. Kiruna-Gebietes," Uppsala, 1915.

[19] V. M. Goldschmidt, "Kontaktmetamorphose im Kristiania-Gebiete."

[20] Th. Vogt, "Geol. Fören. i Stockholm Förh.," Bd. 43, p. 480, 1921.

Examples: Formation of serpentine, talc, sericite, chlorite, kaolin, laterite, zeolites, saussurite, prehnite, carbonates, etc., at the expense of primary silicates.

According to our definition of metasomatism, many important alteration processes, all of which take place with the addition of substances and may properly be regarded as metasomatic phenomena and thus come into this particular class, give rise to the above cited secondary minerals. The formation of sericite from anhydrous silicates frequently is due to metasomatism by hydration, possibly with simultaneous abstraction of some of their original constituents. Furthermore, another special type of sericitization of plagioclase involving the addition of potash is found in the vicinity of many gold-quartz veins.[21] Processes of this kind apparently are closely related to the formation of muscovite from nephelite.[22] We are dealing here with a combination of alkali- and hydration metasomatism.

Phosphorus Metasomatism.—(*A*) Phosphorus halogens interact with silicates rich in lime, forming apatite.

Example: Formation of apatite in contact zones of basic igneous rocks.

(*B*) Soluble phosphates interact with silicates rich in alumina forming aluminium phosphates.

Example: Alteration of silicate rocks under guano deposits.

The example mentioned under *A* often shows, at the same time, replacement characteristic of case *B* of "Chlorine Metasomatism," namely, the formation of scapolite at the expense of plagioclase. Phosphorus metasomatism as illustrated by case *B* has been described from many guano deposits in the tropics.

Carbon Metasomatism.—(*A*) Precipitation of carbon through interaction of silicates rich in iron with CS_2 or COS, forming graphite, iron sulphides and quartz.

Example: Formation of graphite in pyrite impregnations.

The frequent association of pyrite and graphite, both secondary, especially in silicate rocks rich in iron—amphibolites, for

[21] W. Lindgren, "Mineral Deposits," p. 544, 1919.
[22] W. C. Brögger, "Das Fengebiet in Telemark," p. 144.

instance—points decidedly towards their common metasomatic origin. Experimental investigations of the reactions involved in such processes have been carried on for several years at the University of Christiania.

Silica Metasomatism.—Transformation of silicate rocks into opal or quartz with addition of silica.

Silicification of silicate rocks has been reported from many localities[23] and apparently may take place under various conditions. The chemical reactions which lead to silicification are still very little understood. In many cases alumina, a substance whose mobility is generally small, has no doubt been carried away, probably in the form of alkali aluminates.

To the cases of silicate metasomatism described above numerous others might be added. However, this synopsis does not aim at completeness, but only to give an idea of the great variety of metasomatic processes which may occur in silicate rocks.

The various cases of silicate metasomatism described above may occur either alone or in combinations of two or more. Certain of the latter are especially common, as for instance the formation of apatite and scapolite, the simultaneous formation of tourmaline, topaz and greisen, or the metasomatic "syenitization" of granite and the metasomatic formation of ægirite. It may be possible to develop an essentially geological classification of metasomatic processes, operative in silicate rocks, with groups like "Greisen metasomatism" or "Apatite vein metasomatism."

Many cases of silicate metasomatism may properly have to be classed under several headings. Thus metasomatism of muscovite from nephelite may be due to alkali-exchange as well as to hydration.

In classifying "special" cases of metasomatism, a scheme differing in its chemical point of view from the one employed here may be used, as for example, one differentiating between processes of metasomatism involving an exchange of bases, neutralization by acid or basic minerals, or reduction, although in my

[23] W. C. Brögger, "Das Fengebiet in Telemark," p. 544.

opinion, such a grouping would not have any essential advantages.

A PHYSICO-CHEMICAL THEORY OF METASOMATISM.

Considering the great variety of metasomatic processes taking place in silicate rocks, the question naturally arises whether they are controlled by any general laws; and to answer this important question, recourse must be had to physical chemistry. It seems especially important to search for the physico-chemical laws of metasomatism. The law of mass action would seem to apply also to replacements in the world of minerals, and we may ask in what form it might be used to greatest advantage.

Not to make the following considerations too abstract, let us take a concrete example, namely, the metasomatic formation of feldspar at the expense of potash mica. This case belongs to subgroup *B* of alkali metasomatism and has been studied carefully by the writer in the injection contact rocks of the Stavanger region.[24] Metamorphic derivatives of shales have here been subjected to metasomatic feldspathization. The muscovite of the shale reacted with solutions of alkali silicates, forming alkali feldspars. The solutions of alkali silicates added,—a kind of "water-glass,"—were derived from the mother liquors of muscovite-bearing magmas.[25]

The reaction may be expressed by the following equation:

Muscovite	Potash	Silica	Feldspar	Water
$H_4K_2Al_6Si_6O_{24}$	$+ 2K_2O +$	$12SiO_2 =$	$3K_2Al_2Si_6O_{16}$	$+ 2H_2O$

In other words, this is a case where alkali is bound by the "excess alumina" of the precipitating mineral (see above).

[24] V. M. Goldschmidt, "Die Injektionsmetamorphose im Stavanger-Gebiete."

[25] The old distinction between "granite" and "granitite" gains added significance from this. The presence of primary muscovite in a granitic abyssal rock would mean that hydrolysis of the potash feldspar molecules had taken place before the rock was completely consolidated, and was sufficient to cause the separation of muscovite, the residual solution containing free alkali silicate. Metasomatic feldspathization of shales is therefore met with especially around muscovite-bearing abyssal rock masses.

This equation, however, may be somewhat simplified. Water is always present in excess, as we have to deal with reactions in aqueous solutions. Its concentration may therefore be regarded as constant, the solubility of the participating minerals, muscovite and feldspar being at any rate small. We may also presume that there is an excess of silica present, the newly formed as well as the original rocks in the case under consideration containing considerable amounts (about 30 per cent.) of free quartz. Therefore we do not have to deal with a variable ratio of silica to the potash added, but may lump potash and silica together as forming an "alkali silicate." Our equation thus assumes the following simpler form:

$$X \text{ mica} + Y \text{ alkali silicate} = Z \text{ feldspar},$$

and we are, at the same time, not bound to any definite stoichiometric mica formula or any stoichiometric equation whatever. Water is, as pointed out, present in excess.

We may then assume that the alkali silicate solution attacks the original mica which proceeds to dissolve until its total solubility is reached, while alkali feldspar begins to separate out either before or not until this point is reached. As the solubility of the minerals in question is never so great as to permit of all of both minerals, mica as well as feldspar, to go into solution simultaneously, there will at first result a condition of equilibrium with both minerals present. To enable the feldspar to separate out, its concentration in solution must at least equal its solubility, and likewise the concentration of mica, so long as it is present in the original solid state, must also equal its solubility. The concentrations of mica and alkali feldspar in the solvent, during the process of metasomatic replacement, will equal the sum of their individual solubilities in the same solvent. The following equation, as an expression of the law of mass action, must therefore be valid for the condition of equilibrium assumed to prevail during the metasomatism:

$$K = \frac{(\text{Solubility of the mica})^{\alpha} \times (\text{Concentration of the alkali silicate})^{\beta}}{(\text{Solubility of the feldspar})^{\alpha}}$$

where K is the equilibrium constant for the reaction at the existent temperature and pressure.[26]

The equation may also be written in the following form:

$$(\text{Concentration of alkali silicate}) = \sqrt[y]{\frac{(\text{Solubility of the feldspar})^z \, K}{(\text{Solubility of the mica})^x}}$$

This means that at a given temperature and pressure, a minimum concentration of the alkali silicate is necessary to cause the separation of feldspar at the expense of mica. If this minimum concentration of alkali silicate does not exist, the circulating solution can only leach mica, but not separate any feldspar.

This important result may be expressed in a more general form valid for any kind of metasomatism: A solution, in order to effect metasomatism, must contain the substances to be added in concentrations at least equal to a minimum, which is definite for each case.

Analogous reasoning may be applied to metasomatism caused by addition of substances in gaseous form; here a certain minimum partial vapor pressure of the substance added is a condition necessary for replacement.

It is evident that metasomatic processes follow the law of mass action; this has also been emphasized by many authors (*e.g.*, by Niggli in his "Lehrbuch der Mineralogie"). The principle of minimum concentration (or minimum vapor pressure), first published by the writer in the spring of 1921,[27] might aid in the interpretation of metasomatic phenomena by the law of mass action.

We can now understand why metasomatic processes are common, but, lacking in minimum concentration, not universal. Although all the water circulating in the rock crust contains traces of alkali silicate, the potash mica is by no means everywhere changed into feldspar; under definite geological conditions only do the solutions contain so much alkali silicate that the limit concentration of this reaction is reached.

[26] Here we disregard electrolytic dissociation and hydrolysis, as these factors, though of influence in the quantitative relations, are of no consequence in the present, purely qualitative, considerations.

[27] V. M. Goldschmidt, *Geol. Fören. i Stockholm Förh.*, 43, 1921.

Such a use of the law of mass action enables us to conclude what kinds of solutions have been active in a metasomatic process.

The minimum concentration of the solutions naturally differs in different reactions and varies with temperature and pressure. To replace a limestone at high temperatures by chlorides of heavy metals, only a very small concentration of the latter is required, as most of the oxides of the heavy metals are by far less soluble than calcium carbonate.

In some cases of silicate metasomatism we are able to make certain deductions regarding the concentration of solutions involved. Thus we may conclude, from petrological evidence, that a larger concentration of alkalies is needed to convert ferric minerals into ægirite than aluminous minerals into feldspar. This is supported by the fact that ægirite is formed only after all the alumina of a rock has gone to form feldspar.

In this way, certain minerals or mineral associations may be arranged in a definite order regarding their behavior towards definite solutions.

An analogous mode of treatment may be fruitful in cases of minerals formed by non-metasomatic rock-metamorphism.

It is also possible experimentally to establish data important in gaining an understanding of metasomatic processes. Thus, since 1918, I have had made, in this University, a series of determinations of equilibria existing between the sulphides of iron and the common magmatic gases at temperatures between 600° C. and 900° C., the results of which are intended for an early publication. This work will furnish numerical data which throw light on a number of metasomatic reactions in which iron sulphides take part.

It would be of great importance to know whether metasomatic processes in rocks have any tendency towards a definite end-condition. Generally it seems that there is an inclination towards equalization of rock types of "extreme" composition, rocks, with "excess alumina" especially, leaning towards a "saturation" of alumina. Metasomatism, in this way, tends to make rock-masses more homogeneous. The common occurrence of relatively

"indifferent" gneisses among the old crystalline schists, without those marked variations characteristic of non-metamorphic rocks, may possibly be due to such a metasomatic equalization. But this tendency is not general; several metasomatic processes, especially such connected with diaphthoresis, even give rise to "non-saturated" rocks, as in the formation of sericite from feldspars.

What is the motive energy of the metasomatic processes? Its source apparently lies in all those geological agencies which bring rocks of different chemical characters into proximity, or set up potentials between different parts of the earth's crust by variation in temperature and pressure. Hence we find proof of intense metasomatism, especially in contact zones, in the crystalline schists, around ore deposits, and in the zone of weathering.

In still another respect, geological processes have an important bearing on metasomatism. Faults may open convenient passages for circulating solutions, mylonitic crushing of rocks may make quick leaching of large rock-masses possible. Petrology appears here as always to be a geological science.

Metasomatism not only represents a phenomenon whose correct interpretation is of interest to the petrologist and the student of ore deposits; it is also of great geological importance as an essential factor in what we may term the metabolism of the earth.

We may look on geological phenomena as a whole as outward expressions of metabolism on a grand scale, as a perpetual wandering and replacement of material. Two chief groups of phenomena may be distinguished:

An outer metabolism, represented by weathering (in part metasomatic), selective erosion, and sedimentation.

An inner metabolism, resulting in the movements of solid rock-masses and liquid magmas, in gravitative assortment, and finally in metasomatic processes. Thus the metasomatism of silicate rocks is no isolated phenomenon of only local interest, but rather an important link in the metabolism of the earth.

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THE SOCIETY OF ECONOMIC GEOLOGISTS: ITS SPHERE AND ITS FUTURE.[1]

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For many years a feeling has existed among certain geologists who were applying their science to practical purposes that the men who adhered purely to research were so engrossed in their work that they found scant time to call attention to the material usefulness of their discoveries. About two years ago this feeling took form in the organization of the Society of Economic Geologists. This action was not due to any controversy with any other society; on the other hand, the new Society started out with the encouragement and best of good wishes of all allied societies. They all thought that there was a place for it and that they would collaborate with it.

The Society of Economic Geologists has rapidly gotten together, has found itself, and has developed in a remarkable and totally unexpected manner. It has displayed its sphere of usefulness by the papers that have been read at its meetings, by the activities of its committees, by the character of its membership, and by an indescribable educational influence.

To-day this Society contains one hundred and forty-three members. Though it was started in the United States, an important portion of our membership has come from foreign countries—England, Canada, Mexico, Australia, New Zealand, Norway, Sweden, France, Belgium and Japan; and all of these members realize, as do our own members from the United States, that a Society of Economic Geologists has long since been needed the world over, and could work independently but in thorough harmony with the older geologic societies. The Society of Economic Geologists has therefore automatically become an

[1] Opening address by the President of the Society of Economic Geologists, Amherst Meeting, December 28, 1921.

international organization. The badge and the seal which we use to-day, indicating the two hemispheres, is a token of recognition of this world-wide membership.

We have passed the experimental stage; we are a working organization with a rapidly growing influence for good for our members and for industry. We do not seek numbers in our membership; we seek efficiency; we do not seek those who have attained an evanescent notoriety, but we seek only those who have given true and honest work in the application of the principles of geology to the welfare of industry and mankind. We seek friendly relations and meetings where we can come together in the same camp and tent with others whose interests lie in allied directions. Throughout the last two years we have met on different occasions the geologists of other societies. We know that the contact has been beneficial to ourselves and we hope that it has not lacked benefit to those we met.

Economic geology is simply the application of the numerous parts which make up the science of geology. Thus paleontology, stratigraphy, petrology, chemical geology, as well as other phases of the earth sciences, are all connected and inseparable in making up one grand whole, and economic geology uses them all. The specialist in one branch in his intense enthusiasm for his own work may forget and even look down on the work of other specialists, but this is due only to ignorance of what the others are doing, and the fact remains that we are all working in one great field, the earth sciences.

The application of geologic principles in economic problems, however, requires a temperament and education as essential as does the study of the most abstruse problems in any science. No matter how learned a geologist may be, if the ability to apply his science to economic problems is not born in him, or else acquired by long and tedious knocks, he will fail miserably. I have seen many most pathetic cases of this sad result, where theoretic geologists, eminent in their profession as instructors or scientific workers, have been gravely humiliated by utter failure in attempting to do economic work, and have brought disaster both to their

employers and themselves; while in the sphere of theoretic science they have received the world's recognition of their splendid work. Moreover, there is an intellectual, intangible, almost a spiritual side to any purely theoretic feature of the science of geology which must not be ignored and is ennobling in any liberal education.

All branches of geology are so closely related that whether they are studied for theoretic, economic, or for educational purposes, the difference is purely a detail. The theoretic geologist develops facts on which the economic geologist works out material good, and the latter brings data useful to the former; the work of both helps towards that knowledge of the earth priceless in a liberal education. The economic geologist travels widely and continuously from one end of the world to the other; his time is spent in travelling and observing; he sees geologic objects, which the purely theoretic geologist often cannot see, for the latter is mostly occupied in teaching, in laboratory research, and in limited periods of field work. Hence many of the papers published by economic geologists have afforded new material for the theoretic geologist. On the other hand, the economic geologist profits by the work of the theoretic geologist in the latter's development of new truths. The study of fossils by the paleontologist is as necessary in following out certain economic problems as is the work of the economic geologist in applying them.

Thus both the theoretic geologist and the economic geologist become the collaborators of each other. We must admit, however, that certain professional economic geologists, active in industrial work, do not give their fair share to this collaboration. They think that their employer might not like them to do so, or that they have not the time to write. As far as the employer's consent to allow the economic geologist to publish conclusions from specific reports goes, I beg to say that after extended inquiry I know of but few employers who would not grant this permission provided the business details were not divulged. As regards the time that the economic geologist has to write for

scientific journals, the matter is entirely his own concern; but I know of very few such geologists who are so busy that they cannot find time occasionally to write and give the information that they owe to the theoretic geologist, who makes none of the economic profits and works for his science alone.

If the proper equilibrium can be established, neither the economic geologist nor the theoretic geologist will be the debtor; neither will be the creditor; but both will work to their mutual good and self-respect. If such an ideal can be accomplished, and I have no doubt that it will eventually be so, then will the purely theoretic, the purely economic, and the educational feature of the science, progress side by side and to the welfare of all mankind.

We all rejoice that for the second year of the existence of the Society of Economic Geologists we have the pleasure of meeting with The Geological Society of America, and especially in the environment of this great College of Amherst, made famous, among others, by Hitchcock, Emerson, and that honored pioneer in mineralogy, C. U. Shepard. These great men have aided the later work of all geologists, whether purely theoretic or economic, and I am sure that all of us feel it a privilege to meet in the halls where they once taught and where their worthy successor, Professor B. F. Loomis, now presides.

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KANSAS STATE AGRICULTURAL COLLEGE
MAR 29 1922
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EDITORIAL

SOME PRESENT DAY ASPECTS OF THE MINING INDUSTRY IN SOUTH AFRICA.

THE Witwatersrand gold field has always attracted considerable attention from mining men outside its own particular area. It promises in the near future to offer a number of problems, the solution of which will probably be watched with interest in many other parts of the world.

Some of those problems are of a purely technical character; others involve industrial and financial questions of considerable complexity.

In the former class are the various difficulties connected with mining at levels so far attained in but few mines in the world. One of the shafts of the Village Deep Mine has already reached a depth of 6,089 feet, and in six months' time promises to be the deepest in the world. The various problems of haulage and ventilation, arising in connection with working at the City Deep Mine, have been reviewed in a recent paper by Mr. E. H. Clifford, the late consulting engineer to that mine,[1] who discusses in detail the various measures which will be adopted to cope with the unusual conditions involved.

In the latter class come a number of questions of a more general nature, upon the solution of which the future of the Witwatersrand gold field largely depends.

With an output for 1920 valued at nearly 44½ million pounds ($216,270,000),[2] amounting to 49.9 per cent. of the world's production, and with an aggregate output of gold up to 1920 to the value of nearly 647 millions ($3,144,420,000), the field is

[1] *Bulletin Inst. M & M.*, February, 1921.

[2] Conversions to dollars are on the basis of par exchange.

of great importance, even from the world point of view. From a South African standpoint, however, its significance is vastly greater, and the maintenance of the industry at something like the present level is a matter of vital importance to the whole country—a fact only now becoming apparent to the community at large. This will be the better understood when we consider that in 1920 the contribution to the country's revenue, through direct taxation and government share of profits, amounted to £2,170,344 ($10,547,872), while the indirect contribution to the country's revenue, through the medium of railway rates on materials, etc., taxes on the incomes of mining employees, and in a multitude of other ways, was probably much greater still. In addition, the industry distributed in wages in 1920 nearly £17,000,000 ($82,620,000), and spent £14,288,247 ($69,440,880) on materials. It provides the best market for South African products, and proves itself in general a sort of foster mother to most other branches of industry.

In most new countries, mining has been the pioneer industry, and one of the main factors in advancing civilization, and generally preparing the way for other kinds of activity.

In few countries in the world is this so well illustrated as in the Transvaal. The discovery of the Witwatersrand brought the railway into a country which would otherwise have probably been long dependent on more primitive means of transport, and the permanent nature and continually growing importance of the field have since resulted in Johannesburg becoming the most important railway center in South Africa, and one whose traffic is the mainstay of the whole railway system.

The Witwatersrand gold field possesses certain features which are more or less peculiar to it. As already indicated, its relative importance to the country as a whole is probably greater than is the case with any other gold field in the world. Notwithstanding the vast aggregate output, it is, however, as a whole essentially a low-grade field, the success of which depends almost entirely on work being carried on on a large scale with consequent low working costs. Owing to the large number of mines

working in close proximity under very similar conditions, and to the long period over which the field has continued to be productive, with a consequent continual advance in economy and scale of working, the cost of production had, at the time of the outbreak of the war, been reduced to a very low figure, with the result that rock of low grade, which in the earlier days of the field could not have been dealt with, was being mined at a profit. Millions of tons of such low-grade rock had been developed, and, in the case of some of the mines, formed the bulk of the ore reserves. During the war, the continual rise in working costs, chiefly in connection with labor and materials, has rendered the mining of such low-grade ore a matter of increasing difficulty, threatening to bring about the closing down of those mines dependent on low-grade ore. Since 1919, the position has been temporarily relieved by the so-called premium on gold, which was responsible in 1919 for the addition of £3,785,242 ($18,396,276) and in 1920 for £10,670,107 ($51,796,720) to the value of the gold compared with what this would have been at the old fixed rate. That the price of gold will sink to pre-war level does not appear likely for many years to come, but no one doubts that the premium will be gradually reduced, and this will mean the closing down of many mines, unless means is found of compensating for the fall in gold value by reducing the cost of production to something like the former level. The gradual fall in the cost of materials will probably afford a little assistance in bringing this about, but will not materially affect the position. The real key to the situation is generally regarded as lying in some modification of existing labor conditions, and the solution of the complicated questions thus involved forms perhaps the most interesting problem before the South African mining industry to-day.

The question is constantly asked, "What is the life of the Rand?" The answer depends largely on the conditions of working. With working costs at their present level, it is comparatively short, but with a decrease on the demands made upon

it for taxation purposes and the relaxation of labor restrictions, its life may be almost indefinitely prolonged.

One of the most striking features in connection with the South African mining industry during the past two or three years has been the activity displayed in the development of the coal resources of the country, especially in the Transvaal. The conditions induced by the world war brought South Africa into some prominence as a source of bunker and export coal, which, though not perhaps equal to the best British coal, was still a much appreciated and efficient fuel. After a long period of steady, but slow, progress, depending mainly on increasing home consumption, during which the standard of the coal turned out by the collieries has been steadily raised, while but little has been added to our definite knowledge of the coal resources of the country, a period of very active prospecting and development work has recently increased our information enormously in this latter direction. Boring on a more extensive scale than ever previously undertaken has added large areas of coal-bearing country to our known reserves of coal, of the highest South African grades, which were previously rather generally supposed to be confined to comparatively restricted districts.

With the increasing interest which is being taken in fuel questions, and the developments which are taking place in coal products generally, the large extensions of existing coal fields which have recently been proved provide perhaps the biggest field for new enterprises in connection with the mining industry in South Africa to-day. At the same time, the additions to our knowledge of the somewhat unusual conditions under which some of the South African coals were laid down will probably prove of great interest from a geological point of view.

E. T. Mellor.

Johannesburg,
South Africa.

DISCUSSION.

This department has been established by the editors in order to afford to those interested in questions relating to economic geology an opportunity for informal discussion. Contributions are cordially invited either in the form of discussion of more formal papers appearing in earlier numbers or bearing upon matters not previously treated. Letters should be directed to the Editor, Sheffield Scientific School of Yale University, New Haven, Conn. The full name of the author should be attached to all communications.

ESTIMATION OF PETROLEUM RESERVES.

Sir: Concerning the desirability and necessity of stock taking, there can be no question. This applies not only to properly conducted businesses, large and small, but to national and international affairs as well. Of vast importance to any country is a stock taking of its mineral reserves, because much of the world's history has turned in the past, and will depend to even an increasing degree in the future, on the distribution and utilization of minerals.

Concerning the method, or methods, by which stock taking of of mineral reserves can be best or most accurately accomplished, there is room for differences of opinion, a difference which may be of negligible importance in the case of some minerals, but showing a basic divergence in others.

All methods must rest fundamentally on proceeding from the known to the estimated. For these estimates there are available (1) the accumulated information resulting from all the mining development that has been carried on since the beginning of man's written history, (2) a great mass of data representing the work of innumerable investigators since the birth of the science of geology, and (3) the principles which have been evolved and demonstrated by scientific study and research extending over the last century.

With respect to most minerals the factors which need to be

taken into consideration in estimating reserves are definite and well established. In these cases the guide posts lead in such a clear way from the known to the estimated that to one who reads the signs, end conclusions can be reached which have a reasonable accuracy and a commercial value. In the case of the most striking exceptional mineral, petroleum, the known factors are either so small, compared with the broad estimates attempted, or the factors are of such a general character, that the guide posts are indefinite and there is danger of going from the known into a realm where the measuring-stick is made up, to a great degree, of innumerable personal factors.

Petroleum is set apart in two respects from other minerals. In no other mineral does the operator, as a matter of everyday practice, go forth blissfully to develop, by drilling, hitherto unknown deposits lying far beneath the surface. The other and more important difference is that petroleum occupies a paradoxical position among minerals in the respect that new discoveries, new researches and new developments have tended to increase, rather than to decrease, the possibilities of its occurrence in hitherto unsuspected regions. In the early oil development in the United States the Trenton rock was regarded, in certain regions, as the only possible source of oil. Subsequent developments showed that large areas which had been condemned because the Trenton rock was beyond commercial drilling depth, contained important deposits in beds younger than the Trenton. In the same manner it was said by scientists of high standing that the region which later became the great California oil fields could not yield oil in commercial quantities, because the strata were too young, too broken, and too intimately associated with volcanic rocks.

In other minerals the increase of exact information has resulted in defining and limiting the condition under which they may occur. The mere finding of fossils of one of several different ages to-day justifies the statement "no coal occurs in these beds." On the contrary, the growth of knowledge with respect to oil has been to progressively extend its known range through rocks of different ages and to multiply the variety of

conditions under which it may occur in commercial quantities. To mention only one example that varies from the first pseudo-deduction: It is natural to consider that, because of the fluid character of petroleum, intricate faulting would be fatal to its occurrence in commercial quantities, but it has been demonstrated that the fundamental condition in two important oil-fields is a very complicated system of relatively small fault blocks.

It is now known that petroleum deposits may occur in sedimentary beds of any age from the oldest to the youngest, except those portions which are so metamorphosed that they are incapable of retaining oil. As the greater part of the world's surface is composed of sedimentary rocks, so the problem of estimating the oil reserves of the world becomes a broad one. Much is known with regard to the sedimentary rocks of the world —for example, the distribution of the rocks of different ages has been elucidated to a great degree, and there is an immense amount of scientific data representing the work of innumerable investigators, but with respect to the greater part of the world, all this is inconclusive from a petroleum standpoint. This is true not only in areas in which no detailed geological work has been done, but also in many regions which have been investigated with care from a general geological standpoint, or with respect to some other mineral.

On the other hand, in proven fields immense progress has been made in the past few years in the accurate estimation of reserves and highly perfected methods have been developed. In such territory it is now possible to make estimates with great accuracy, but these highly refined and exact methods are not applicable in the quantitative estimation of oil possibilities over wide areas, because one does not possess, and cannot secure in advance of a considerable amount of drilling, the exact data required by these methods of estimation.

The aggregate area of all the actually producing oil acreage of the world is insignificant. How then can one proceed from this strikingly small total area of the known to the vast area to be estimated, represented by the whole unmetamorphosed sedi-

mentary rocks of the world within five thousand or six thousand feet of the surface? One is tempted to proceed by analogy and one can, by this means, build up a formidable structure in which the component parts are, from the very broadness of the factors on the one hand and the very limited scope of exact knowledge on the other, largely personal equations contributed by a great number of minds. Such a method inevitably leads to underestimation, for the very simple reason that a developed region naturally looks larger and receives greater weight than an undeveloped one. If one had endeavored to estimate the petroleum reserves of Oklahoma in 1890 by analogy with the developed eastern fields, only a very rash man would have placed them at anything but an insignificant fraction of those since revealed. If, at the same time, one had attempted to estimate the petroleum reserves in the undeveloped portions of California by analogy with the producing regions in that State, there could have been only one result—and yet we possessed in 1890 much more knowledge with respect to Oklahoma and California from an oil standpoint, than we possess to-day with respect to the greater part of the world.

If in 1900 the oil reserves of the coastal plain east of the Mississippi had been estimated by analogy with those west of the Mississippi, both would have been negligibly small. If to-day an attempt is made to estimate the petroleum reserves east of the Mississippi by analogy with the demonstrated oil contents of the region west, what is the result?

This suggests another feature of the analogy method. The estimate of the aggregate petroleum reserves west of the Mississippi in the coastal plain having been determined by a series of analogies, in other words to paraphrase a legal phrase, having compounded the analogy, one then uses it as a basis for another analogy without ever being able anywhere along the line to get away from the subconscious psychological control factor that a producing field necessarily looks bigger than one that is not producing.

One wonders whether more useful and defensible end-results

could not be secured in dealing with large units, by proceeding from the known to the estimated by a simpler route, which will reduce to one or two the innumerable personal factors that are inextricably involved in the compounded analogy method.

In formulating a fundamental basis for the estimation of oil reserves in wide areas, one would consider:

(*a*) Certain regions have now been developed to a point where, with respect to producing areas and the adjoining barren areas, oil men will agree that all of their possibilities are accurately known. Seeking then to start from that which is known, one would select in (1) the Eastern, (2) the Oklahoma, and (3) the California fields the largest obtainable compact block containing both productive and barren areas whose possibilities had been demonstrated beyond any possible doubt, and derive from each of these a factor representing the average oil content per cubic mile, and then combine these three into a mean factor. This initial factor would be most satisfactorily determined by a committee working together.

(*b*) Having thus established a factor from the known, one would proceed to the unknown by seeking to establish the factor of chance represented by a common fraction. For the determination of this latter a competent committee working together is required. One method might be to take the sedimentary rocks of the world as a whole, and the accumulated knowledge of oil development up to the present time and endeavor to fix whether one wild-cat well out of fifty or one hundred, or two hundred, or five hundred, or whatever other number may be fixed, will on the average encounter commercial oil within a depth of, say, one mile.

(*c*) One would then proceed to the broad factor which has been established, that commercial deposits of oil may occur in sedimentary rocks of any age, excepting those which have been so metamorphosed that they are non-oil-bearing, and taking the present knowledge of the distribution of rocks and the extent of metamorphosed areas, determine the cubic contents of the possible oil-bearing rocks within one mile of the surface in the area

to be estimated, and then, to obtain the end result, apply the factor established by combining the mean factor established in (*a*) with factor (*b*).

Such estimates would be revisable from time to time, as the growth of knowledge fixes more exactly the factor of chance, and as the exact area of possible oil-bearing sedimentary rock becomes more accurately determined by continued research. It is felt that important revisions of such estimates will arise more from an increase in the exact determination of the variable (*b*) than by any great alteration in the value now given to (*c*).

While it is true that the analogy method, for the psychological reason indicated, gives estimates which are necessarily too low, and while it is also true that oil in commercial quantities may be found in sedimentary rocks of any age from the oldest to the youngest, and in a constantly increasing variety of structural conditions, this does not mean in any sense that the oil reserves of the world are limitless.

The greater part of the sedimentary rocks of the world will be found not to contain oil in commercial quantities. The search for oil will involve tremendous expenditures and there will be many failures, as well as the discovery and development of many new oil-fields, but it is likewise true that every barrel of oil produced brings the world just that much nearer the exhaustion of its petroleum supply. The startling increase in the production and consumption of petroleum has been one of the striking features of the present era of industrial development, and the result is that at the present time the oil reserves of the world are more nearly exhausted than are those of any other important economic mineral, with the possible exception of anthracite. The situation deserves careful and serious consideration, and in forcing a wider realization that the supply of petroleum in the world is not inexhaustible and in bringing home the necessity of conservation, by which is meant proper development and utilization, those who have attempted serious estimates of the petroleum reserves have rendered a great public service. That the estimates have been misused and that they have invited certain conclusions,

which, though perhaps natural, are unwarranted, is most unfortunate and regrettable, particularly since a reaction has set in with a tendency to regard these estimates as but a cry of "Wolf! Wolf!"

The country was startled a decade or two ago by certain scare-head statements regarding coal, converted into a term of years based on estimates and a small fraction of a curve of industrial tendencies. This period has passed without the scare-heads being realized, even in a small degree. The purpose was laudable, but the result ludicrous, not because the estimates were unworthy or in this case lacked reasonable accuracy, or because there was not a need to press for proper development and utilization, but because of entirely unwarranted use of a limited portion of the curve of industrial tendencies which was not characteristic and which, one is sorry to say, the estimators did not regard as characteristic, but which they used to secure publicity.

The petroleum estimates have likewise been converted into a period of years with more or less safeguarding and qualifying statements which are overlooked by the majority of users. These periods of years, taken literally, have been translated into terms of progressive exhaustion, and this again into the co-related increase of price. This process, while natural, is equally unwarranted by the facts. Thus, some have reached the conclusion that the estimates, and the scare-heads resulting therefrom, were responsible for the period of over-production in the United States which is just drawing to its close, and for the disastrous drop in petroleum prices which this over-production entailed. While these estimates cannot be fairly charged with being the fundamental cause of this over-production, which resulted primarily from an entirely different set of factors, they, unfortunately, afford a convenient kicking-post.

The attempt to express exhaustion in terms of years is a favorite one, but the simple arithmetic process commonly employed is, in the case of oil, extremely fallacious, because it quite ignores a number of fundamental economic factors. Long before the world has reached a stage when high prices will fail

to bring temporary over-production—and I believe that time is more distant that some recent estimates indicate—petroleum prices will approach the economic limit, which will, on the one hand, curtail certain uses of petroleum products, and, on the other, will make it commercially feasible to manufacture substitutes for many petroleum products, or to derive them more extensively by distillation from the very widely distributed oil-shale deposits, or what is probably a much more important source—the high-volatile coals.

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THE PROFESSION OF ORE HUNTING.

Sir: Mr. Augustus Locke's paper on "The Profession of Ore Hunting" (vol. XVI., 1920, p. 243) deals admirably with several aspects of the subject. He recognizes that the mining geologist fails as an ore-finder, but it may be doubted if sufficient stress is laid on what I believe to be the main cause of this failure. The scientific equipment of the mining geologist of today, even when he has learned all that most of our teachers have to impart, does not warrant him to pose as a *finder* of ore.

The fundamental principles of ore deposition are not understood. The mode of combination or solution in which primary ore and gangue minerals segregate from magmas in the first instance we do not know, and our knowledge of the cause of their development as solids in veins or other deposits is far from satisfactory. We know that water is essential in the formation of ore deposits, but there is no certainty as to how it acts. That its function is merely physical and not chemical is open to very grave doubt. It is practically certain that the phenomena of the occurrence of ores have a significance which, if appreciated, would be of enormous value to the mining geologist.

What do we know of the cause of the formation of fissures the contents of which provide so much of our ore? Some say

they are the result of contraction, others that they are caused by expansion.

Of the fundamental facts or theory of ore deposits we know practically nothing definite. The only really explicit theory we possess, viz., that of the pneumatolytic origin of the high temperature ores—one regarded as almost sanctified by over seventy years of belief—depends on premises that are almost certainly false.

It is by experiment only that there appears to be any possibility of our establishing economic geology as a real science. We must seek the aid of geochemistry and geophysics, and the men who do the work can not expect adequate reward.

A commencement should be made with the high temperature ores, since we know them to be of direct magmatic origin.

The mode in which silica travels in the liquid state and its relation to water, which invariably accompanies it, must be determined. The solution of this problem, which should not be difficult, will mark important progress toward determining how gangue minerals are formed. Gradually the significance of the existence and of the form of particular minerals will be revealed. We must ascertain how tin and tungsten are transported and how deposited. The study of copper and the other base metals follows. Experiment would soon indicate the approximate temperature and pressure conditions under which minerals develop and the relation of these factors to ore deposition.

The urgency of the necessity for experimental work is generally admitted and under competent direction important results are certain.

Mr. Locke believes the money for research will come from mining companies. This is desirable, certainly, but I cannot regard it as likely in the case of the "inventor geologist" studying pure science. The prospect of profit is too remote to attract the mining capitalist. It appears to me that the work should be commenced either by government or existing research institutions. As soon as the possibilities of the practical application of the principles thus established were demonstrated mining com-

panies would not be slow to provide funds with which to develop them.

The weakness and faults of many mining geologists are, I venture to submit, mainly due to ignorance of general principles. Empiricism scores against science because the latter is often vague and inadequate.

The factors, according to my opinion, which bring success to mining geologists are, in the order of their importance, first luck, second experience, and third scientific knowledge. The contempt of the old prospector for science and its exponents is not entirely unreasonable. When theory and practice clash theory is usually either fundamentally wrong or misapplied.

The foundation on which the science of mining geology must be built is a knowledge of: the cause of formation of the cavities now occupied by ore; under what conditions of solution ore was introduced; the approximate temperature and pressure limits within which ore minerals developed; and the significance of the presence and form of the various gangue minerals.

J. Morrow Campbell.

Maymyo, Burma.

OCCURRENCE OF GYPSUM IN THE GULF COAST SALT DOMES.

Sir: On account of the paucity of the literature on the subject, it is difficult for a writer not familiar with the Gulf Coastal region of Louisiana and Texas to obtain accurate information concerning the occurrence of gypsum and anhydrite on the salt domes. The following remarks may form a pertinent supplement to Mr. Newland's interesting paper on the "Geology of Gypsum and Anhydrite" (No. 6, vol. XVI., Sept.–Oct., 1921).

The accuracy of the records of the occurrence of gypsum at depths of 1,000 feet or more in the salt domes is questioned by Mr. Newland. On the Gulf Coast the drillers do not distinguish between gypsum and anhydrite. Much of the gypsum that is reported in the logs is anhydrite and the writer is of the opinion

that the anhydrite may be the much more common of the two. But gypsum does occur and at very considerable depths. The writer has before him cores of massive selenite from depths of 750–850 feet at Bryan Heights. He has seen cores of gypsum from depths of somewhere between 960–1,300 feet at Stratton Ridge. Some of the cores had selenite with cleavage faces 5–6 inches in diameter. He has seen gypsum cores from Sulphur, La. The exact depth from which the cores came is not known, but is somewhere below 700 feet. At West Columbia gypsum-selenite-anhydrite cores have been obtained from depths of around 800 feet. At Damon Mound there is much massive selenite, but at the relatively shallow depths of less than 500 feet.

At Palangana masses of fragments of selenite have been obtained off the bit respectively in the Nat. Oil Co.'s, Schallert No. 3, from around 3,500 feet and in the Humble O. R. Co.'s, Singer No. 2, from 1,820 feet. At the Markham salt dome some selenite was obtained from around 2,000 feet in depth. The thickness and amount of the selenite in these three cases is not known to the writer. At Blue Ridge a large fragment of a single crystal of selenite, in size some 4 x 2 x 1 inches, was obtained from a depth of below 3,400 feet in a Sinclair O. & R. Co. well. The fragment had apparently been embedded in clay, and was not from any bed of gypsum. Gypsum ordinarily is spoken of by the Gulf Coast geologists as forming part of the cap rock at Humble, Spindletop, Big Hill-Matagorda, Hoskins Mound, South Liberty-Dayton. These are all domes with deep-seated caprock, but the writer is not sure how much of the reported "gypsum" actually is anhydrite.

Mr. Newland believes that it would be difficult for the gypsum to have crystallized from solution under the rock pressures corresponding to the indicated depths and suggests that such gypsum is more likely an after effect of the arching of the limestones through another process. It is very doubtful if the gypsum was the original form in which the calcium sulphate was deposited. Anhydrite, in the writer's opinion, is probably the more common form, and on some domes, such as North Dayton, Hoskins

Mound, and Big Hill-Matagorda, is reported to be accompanied by very little gypsum. In these domes, when the latter occurs, it is as small veins and stringers in the anhydrite. Wherever the writer has seen the contact of the gypsum and the anhydrite, the former has been secondary, and apparently an alteration product of the anhydrite. The selenite commonly fingers out into the anhydrite and there are transitions between the granular saccharoidal anhydrite, granular gypsum with the same texture as and apparently pseudomorphic after the anhydrite, and coarsely crystalline selenite.

That the deposition of the anhydrite is connected with limestone has in no way been proved and in the case of many domes is extremely doubtful. At Damon Mound, Hoskins Mound, Bayou Heights, Sulphur, Spindletop, the anhydrite and gypsum occur in conjunction with limestone, and a priori, the hypothesis seems attractive that the limestone may in part have been replaced by the anhydrite. Little careful study has been made of the caprock and the relations of the limestone to the anhydrite and gypsum are in no way known. In the few cores from Bryan Heights, which show limestone and gypsum, the former is the younger and fills fissures and cleavage cracks in the selenite. At North Dayton, at West Columbia, above and below a 150-foot sill of salt at 3,350 feet at Palangana, possibly also Stratton Ridge, the anhydrite occurs without any known mass of limestone, and in these cases it is difficult to attribute the deposition of the anhydrite to any affect of limestone.

DONALD C. BARTON.

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REVIEWS

The Geology of the British Empire. By F. R. C. Reed. Edward Arnold, London.

The question likely to be asked by anyone on first seeing the title of this book is what reason is there for publishing a treatise dealing exclusively with the geology of the widespread and widely separated parts of this vast Empire. What bearing has nationality on geology, or *vice versa?* What special geological problems, for instance, have Australia and Canada in common? The answer is that the Great War has knit the constituent parts of the British Empire more closely together. Each Dominion, Crown Colony or Protectorate tends to take more interest in the other parts of the Empire than in days gone by. Economic geology and mineral resources have become very important subjects. One of the great lessons that the War taught was that the British Empire should exert every effort to be self-contained as far as possible in regard to supplies of minerals and facilities for refining them. To do this successfully requires in the first place a knowledge of the geology of the constituent parts. Mr. Reed has performed a good service in writing this summary of the geology of the Empire.

In reviewing a book covering the geology of such vast regions all that one can do is to test it as regards the districts or regions with which he himself is familiar. Tested on this basis the present reviewer has no hesitation in saying that the author has been very successful. Many works on geology offer little for criticism in parts dealing with phases of the subject with which the authors are familiar. But when the authors summarize reports or papers of others on districts or regions with which the authors themselves are not familiar many otherwise valuable publications exhibit inaccuracies and wrong conclusions. Wrong interpretations are made, and important and unimportant matters are not dealt with in proper proportions. It can be said that Mr. Reed has been more successful than most authors in this respect. His summaries are excellent and he has grasped the spirit of the subject.

The book, consisting of 480 pages, is published in an attractive form and is well illustrated with maps and diagrams. To Canada and Newfoundland together are allotted 61 pages. The arrangement of the subject matter is good. The geology is first dealt with under the heading

General Characters and then under Details of Stratigraphy. Following these are useful notes on economic geology. In the reviewer's opinion these notes might be expanded with advantage in later editions. At the end of the volume a summary two or three pages in length might be given of the mineral resources of the Empire as a whole, showing the supplies, production and comparative standing.

The book will be useful for travellers visiting various parts of the Empire. A few years ago the reviewer visited one of the more important of the Dominions, but found there was no book available dealing with the geology as a whole and the mineral resources. Individual States had excellent reports on numerous areas and districts, but there was no general work which would indicate to the visitor how and where he could spend a few weeks to the greatest advantage. Mr. Reed supplies this need. His useful summaries are accompanied by references to the more important literature and by maps which will be of great assistance to the traveller. With this book in hand the traveller to any part of the Empire can in a short time obtain the information he desires without having to look up and wade through numerous reports. With the exception of the British Isles themselves, descriptions of the geology of all parts of the Empire are given—the rock of Gibraltar, the Falkland Islands, St. Helena, Hong Kong, all are included.

WILLET G. MILLER.

TORONTO, CANADA.

Bulletin No. 1, Idaho State Survey. Bureau of Mines and Geology. "The Copper Deposits of the Seven Devils and Adjacent Districts" (including Heath, Hornet Creek, Hoodoo, and Deer Creek). By D. A. LIVINGSTON and F. B. LANEY. 105 pages, 13 plates, 11 maps, including two large pocket maps.

This report begins with a general description of the Seven Devils quadrangle, including its geographic location, physiography, scenery, climate and a brief history and summary of production, followed by a discussion of the general geology.

The ore deposits are classified under four heads: (1) Mineralized Shear Zones, (2) Fissure Veins, (3) Disseminated Deposits of Large Size, and (4) Contact Metamorphic Deposits. Under each division the nature of the deposits falling under that caption is taken up in detail; for instance, under contact metamorphic deposits, the most important and extensive type of the region, the writers discuss fully the rocks involved—the contact minerals, and the ore minerals, hypogene and supergene. This discussion is followed by descrpitions of the mines and prospects falling under that classification, arranged in alphabetical order, treating each more or less fully according to its relative importance. To

cite a specific example, the Peacock Mine, of which is given its history and production since its discovery, its development and the occurrence of the ore together with a sketch map showing a plan of the workings, topography, and the areal geology.

At the end of the bulletin four adjacent districts are described: the Heath District, North Fork of Hornet Creek, the Hoodoo District, and the Deer Creek District. The descriptions of these districts are accompanied by sketch maps showing the extent of the workings and the areal geology.

In reviewing this bulletin, due consideration must be given the fact that only inadequate facilities were available to the publishers, with the inevitable result that cuts and typography are not as perfect as could otherwise be obtained.

The type is distinct and quite free from errors, but the material could be better margined, and the spacing between lines made more uniform. The maps are well executed with the exception of pocket map No. 2, which is apparently so much reduced as to make the closeness of the contour lines obscure the areal geology pattern. The half-tone cuts are not only indistinct and poorly arranged on the pages, but also indicate a faulty selection of material to illustrate the features intended. A more pleasing bulletin would have resulted had most of the half-tone cuts been omitted.

The subject matter of the bulletin is well classified and coördinated, but in places has the undesirable feature of unnecessary repetition. On the whole, the bulletin serves a useful purpose. It is complete and the material is treated in considerable detail. W. H. BRADLEY.

A Manual of Determinative Mineralogy with Tables for the Determination of Minerals, etc. By J. VOLNEY LEWIS. Third Edition. Revised and enlarged. Pp. v + 298. Figs. 81. Cloth. New York, John Wiley & Sons, 1921. Price, $3.00.

In this, the third edition of Professor Lewis's "Determinative Mineralogy," the value of the book has been increased by the addition of a list of minerals classified in accordance with their physical properties. In this list are the names of 290 minerals. Each mineral is described briefly, but with sufficient fullness to enable the student to test the results of his blowpipe work. The major portion of the volume deals with the use of the blowpipe for identifying minerals. In arrangement of the subject matter this edition is similar to the earlier ones. Since nearly all the errors and misprints in the earlier editions have been corrected, the book is now one of the most satisfactory treatises on qualitative blowpipe analysis of minerals in English. W. S. BAYLEY.

SOCIETY OF ECONOMIC GEOLOGISTS

This department has been established for the official communications of the Society of Economic Geologists whereby the affairs of the Society such as notices, minutes, titles of papers, elections, etc., may be brought regularly to the attention of its members.

ANNOUNCEMENT.

The Council of the Society of Economic Geologists and the Directors of the Economic Geology Publishing Company have entered into an agreement whereby the journal, ECONOMIC GEOLOGY, becomes the official organ of publication for the Society of Economic Geologists. Papers presented before the Society and accepted for publication by its Publications Committee and the Board of Editors of ECONOMIC GEOLOGY will normally appear in this journal unless the author prefers publication elsewhere. Such papers shall be designated with the name of the Society, and for the present reprints of such papers will be sent by the Society to each of its members—thereby providing members with the Society's publications. The Society will thus through its Publications Committee transmit all accepted manuscripts to the Economic Geology Publishing Company for publication.

The above arrangement is in no way to affect the previous independent status of the journal, and, as before, manuscripts are desired from our domestic and foreign clientele regardless of whether they may be members of the Society of Economic Geologists. The greater proportion of the subscribers to the journal are not members of the Society and they will thus benefit by the articles which will appear from the Society. The arrangement is one which should prove satisfactory to the journal, ECONOMIC GEOLOGY, to its subscribers, and to the membership of the Society of Economic Geologists.

EDITOR.

NOTICES.

Officers of the Society for the year 1922 are:

President,	Waldemar Lindgren.
Vice-President,	Ralph Arnold.
Secretary-Treasurer,	Sydney H. Ball, 42 Broadway, New York City.
New Councillors:	James F. Kemp and C. K. Leith.
Executive Committee:	The President, The Secretary, R. A. F. Penrose, Jr., Arthur C. Veatch, Alan M. Bateman.

Since the publication of the list of members in the "Summary of the Proceedings of the Society of Economic Geologists" for 1920–1921 the following have been elected:

Roderic Crandall, Port Washington, L. I.
Frank L. Garrison, 982 Drexel Bldg., Philadelphia, Pa.
John B. Mertie, Jr., U. S. Geological Survey, Washington, D. C.
Louis E. Reber, Jr., Chief Geologist, United Verde Copper Co., Jerome, Arizona.
Ralph H. Soper, Sinclair Exploration Co., 55 Liberty St., N. Y.
Eugene C. Templeton, Box B, Downey, Calif.
Paul Weaver, Chief Geologist, Cia Mex. de Petr. El Aguila Apartado 150, Tampico, Tamps. Mex.

The next winter meeting of the Society will be held in conjunction with the annual meeting of the Geological Society of America at Ann Arbor, Mich., in December, 1922.

SCIENTIFIC NOTES AND NEWS[1]

E. De Golyer has returned from a trip to the Mexican oil fields.

Chester W. Washburn has returned to New York from an extended South American trip.

W. J. Mead, of the department of geology, University of Wisconsin, gave a course of twelve lectures in metamorphic geology at the University of Chicago during the first half of the winter quarter.

Robert Anderson, who is a director of the Whitehall Petroleum Corporation, Ltd., of London, has recently returned to this country from abroad, having arranged from now on to have part of his time for independent scientific work. He is now at his home in Menlo Park, California, and is carrying on some research work at Stanford University.

George H. Garrey, of Philadelphia, is in Tonopah, Nevada.

J. E. Spurr, editor of the *Engineering and Mining Journal*, has been in San Francisco recently arranging for the consolidation of the *Engineering and Mining Journal* and the *Mining and Scientific Press*.

C. M. Keeler has been appointed valuation engineer in the Oil and Gas Section of the Federal Internal Revenue Department.

Walter Harvey Weed has completed examinations in the Porcupine district, Ontario.

James R. Finlay has returned to Los Angeles from New Mexico, where he has been making a valuation of the mines for the purpose of taxation.

W. F. Ferrier, of Toronto, was a recent visitor at New York and New Haven, collecting specimens for the new museum of the University of Manitoba, Canada.

T. Pryor is engaged on a geological investigation of the mines of the Kolar Gold Field, Mysore State, South India. This field is of particular

[1] Geologists, mining engineers and others interested in applied geology are invited to keep the editor informed of new investigations of mining districts or scientific studies undertaken by them, together with such other scientific and personal items as may come to their notice.

interest because the 66th level of the Ooregum Mine is 5,967 feet vertically below the surface.

H. M. Eakin, of the U. S. Geological Survey, has completed his report on the Juneau district, Alaska, and has left Washington.

F. J. Katz returned to the U. S. Geological Survey March 1 to take the place of R. W. Stone.

Robert T. Hill has temporarily closed his office at Dallas pending the completion of some manuscripts and is now at 623 N. Central Avenue, Glendale, California.

F. R. Weekes will be in Venezuela until the middle of April carrying on professional work there.

J. Mackintosh Bell is in London.

G. R. Mansfield, of the U. S. Geological Survey, has returned from Porto Rico.

F. Lynwood Garrison has returned from Canpeche, Mexico, where he has been examining oil lands, and is now in Philadelphia.

Bradley Stoughton has been elected president of the Yale Engineering Association. Formerly he was secretary of the American Institute of Mining and Metallurgical Engineers.

Solon Shedd, head of the department of geology at the State College of Washington, and State Geologist of Washington, returned to Pullman, Washington, from Stanford University, where he has been giving lectures in geology during the summer and autumn quarters.

Harold A. Linke has returned to Salt Lake City after a year's work at Pachuca, Mexico.

E. F. Davis, formerly with the Matador Petroleum Co. of Cheyenne, Wyoming, is now with the Shell Co. of San Francisco in the geological department.

Edgar Kraus is making his headquarters at Houston, Texas, as geologist for the Atlantic Oil Producing Co., but is continuing his work in the Gulf Coast district.

A. W. Jenks, who has been examining mineral properties in northern Ontario, has returned to New York.

Lucien Beckner, petroleum geologist of Winchester, Kentucky, has been appointed colonel on the staff of Governor Morrow of Kentucky for

services rendered the State of Kentucky in the development of its natural resources.

M. R. Campbell, of the U. S. Geological Survey, as a result of a recent examination in the Deep River Coal Field of North Carolina, shows that one tract containing 15 million tons of high-grade coal has been definitely outlined, and estimates that in the remainder of the field there is at least 60 million tons of coal available above 1,500 feet depth.

B. Prescott is making geological examinations in the Sierra Mojada district, Mexico.

W. Armstrong Price, formerly paleontologist for the West Virginia Geological Survey and lately with the Transcontinental Petroleum Company in Tampico, has returned from Mexico and is engaged in subsurface studies for F. Julius Fohs, chief geologist of the Humphreys Oil Company, at Dallas, Texas.

A. Crandal, who has recently spent some time in Africa, has returned to the United States.

Edmund B. Stiles, formerly with the Subsurface Department of the Bureau of Economic Geology, University of Texas, is now engaged in subsurface work with F. Julius Fohs, chief geologist of the Humphreys Oil Company, at Dallas, Texas.

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